Memo

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Contact person
Ebi Meshkati Shahmirzadi

Direct number
+31(0)88 335 7965

E-mail
ebi.meshkatishahmirzadi@deltares.nl

Subject
Literature review and conceptual model for the ripening of mud

1 Introduction

This memo contains a concise literature study on the ripening of mud. It builds upon the state-of-the-art literature studies executed in the scope of, or adjacent to, *Kleirijperij* and *Markerwadden* projects (Sjenitzer et al., 2018; Talmon et al., 2018). It extends the knowledge discussed in these two literature surveys by also considering the effect of biological and (bio-) geochemical processes. Furthermore, we address how mechanical treatment of the mud influences the ripening process.

This memo aims at providing a comprehensive overview of the processes affecting ripening. We assume ripening starts with fresh mud, which develops into ripened soil over time (Figure 1). This end point depends on the foreseen application of the ripened soil, as the application determines the mechanical properties it should have.

In Section 2, we define what ripening is and divide the process into different phases. For each phase, we discuss the driving forces, key parameters, possible interdependence and related timescale (Section 3 and 4). Section 5 discusses how to model these different phases. To conclude, Section 6 provides an overview of the dominant processes, possible knowledge gaps and the different timescales associated with the ripening process.

Figure 1: The start and end point of the ripening process: from fresh mud (left panel) to ripened soil with suitable mechanical properties (right panel). Photos taken from the Kleirijperij pilot project.

2 Ripening

2.1 Definition of ripening

Ripening is a soil formation process that irreversibly converts waterlogged sediment into soil by desiccation and structure development (Vermeulen et al. 2003). An alternative international name for the Dutch term 'ripening' is 'initial pedogenesis'. Ripening of dredged sediment consists of physical, chemical and biological processes. Van der Meulen (2012), citing Pons and van der Molen (1973): "In addition to physical ripening, there are chemical ripening and biological ripening. Despite that the three processes take place parallel and spontaneous, physical ripening is the governing process".

Rijniersce (1983) defined physical ripening as: "a soil forming process by which a sediment that is exposed to drier hydrological conditions than those with which it can maintain equilibrium is practically irreversibly converted into more compact, aerated, more permeable material. The physical properties of which depend on the new hydrological conditions and which can be designated by the name soil". Not every soil can ripen in practice. Only soil with a clay content greater than 8% and/or organic matter content higher than 3%, will be able to ripen (Pons en Zonneveld 1965).

2.2 Phases in the physical ripening process

From a purely mechanical point of view, the ripening process is about dewatering of fresh mud to an extent that it becomes a soil with suitable mechanical properties (e.g. consistency and bearing capacity) for a given engineering application e.g. material for dike, uplifting lands, agriculture etc. This implies that evaluating whether a certain soil has ripened enough depends on requirements of the application. For most engineering applications, under self-weight and in absence of (bio-chemical) additives, a fresh mud deposit undergoes three main phases during the ripening process:

- (hindered) settling (Section 3)
- self-weight consolidation (Section 3)
- desiccation (Section 4)

What these three phases have in common is the flux of water from within the mud deposit to outside of the mud deposit which results in a denser deposit. However, the driving force behind this water flux differs. For settling and self-weight consolidation, the driving force is gravity. For desiccation, it is surface evaporation. We have grouped the explanation of these different phases by driving force, hence settling and self-weight consolidation are discussed in Section 3 and Desiccation is described in Section 4.

Figure 2 schematically shows the ripening process and the timing of the different phases. The time scale of the different phases is also indicated. Note that the x-axis scales logarithmically. The settling and first consolidation phase are very short compared to the second consolidation and desiccation phase. These terms are described in more detail in Section 3 and 4.

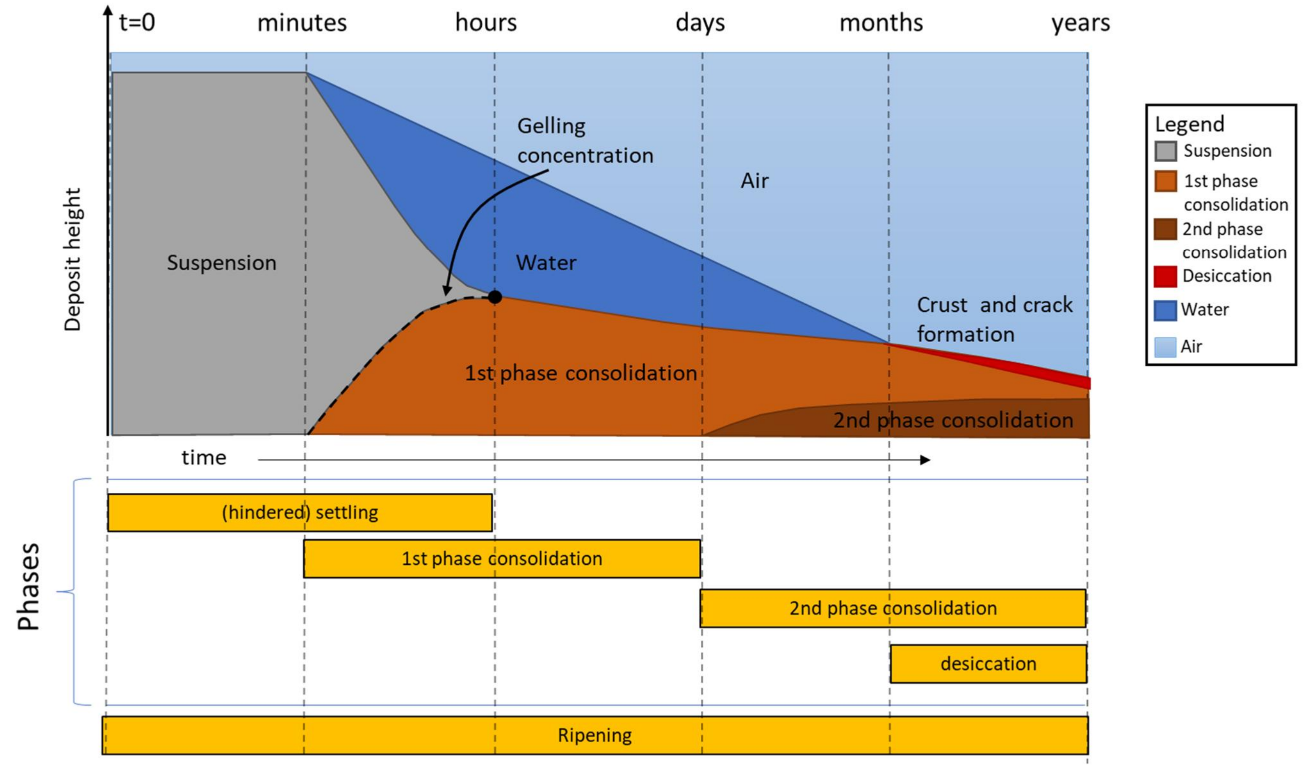

Figure 2 Schematic representation of the ripening process, indicating the different phases and their chronology. Associated timescales for the different phases are also indicated. Adapted from Talmon et al. (2018)

Figure 3 provides a more detailed conceptual sketch of the different phases in the ripening process. We indicated the flow of water through the deposit and the driving force. In this sketch we assumed that water expelled from the deposit through consolidation can be drained both through the top and bottom of the deposit. In the last phase (rightmost sketch) a crust has formed and cracked. More details on crust and crack formation are provided in Section 4.

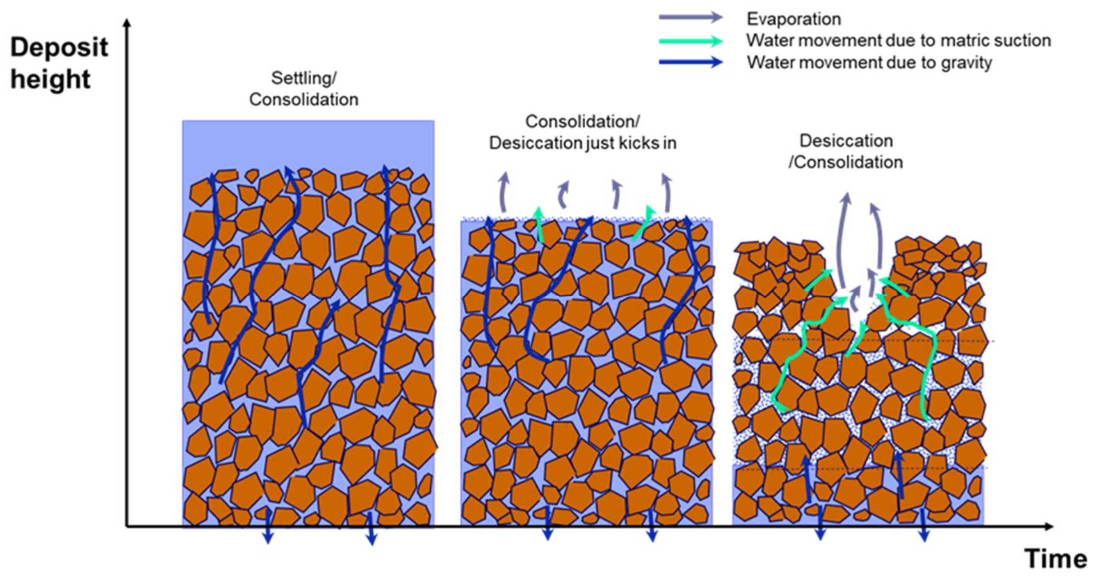

Figure 3 Sketch of driving forces expelling water out of the deposit during different ripening phases.

Figure 4 gives a high-level overview of all the phases, steps and governing processes a fresh mud undergoes while transforming to soil. In this flow chart, the main phases and their sub-phases are each labeled with a distinct color code. Furthermore, they are accompanied by a card listing the driving force, key parameters and how to approximate the combined effect of key parameters. These phases and processes are described one after each other throughout this manuscript.

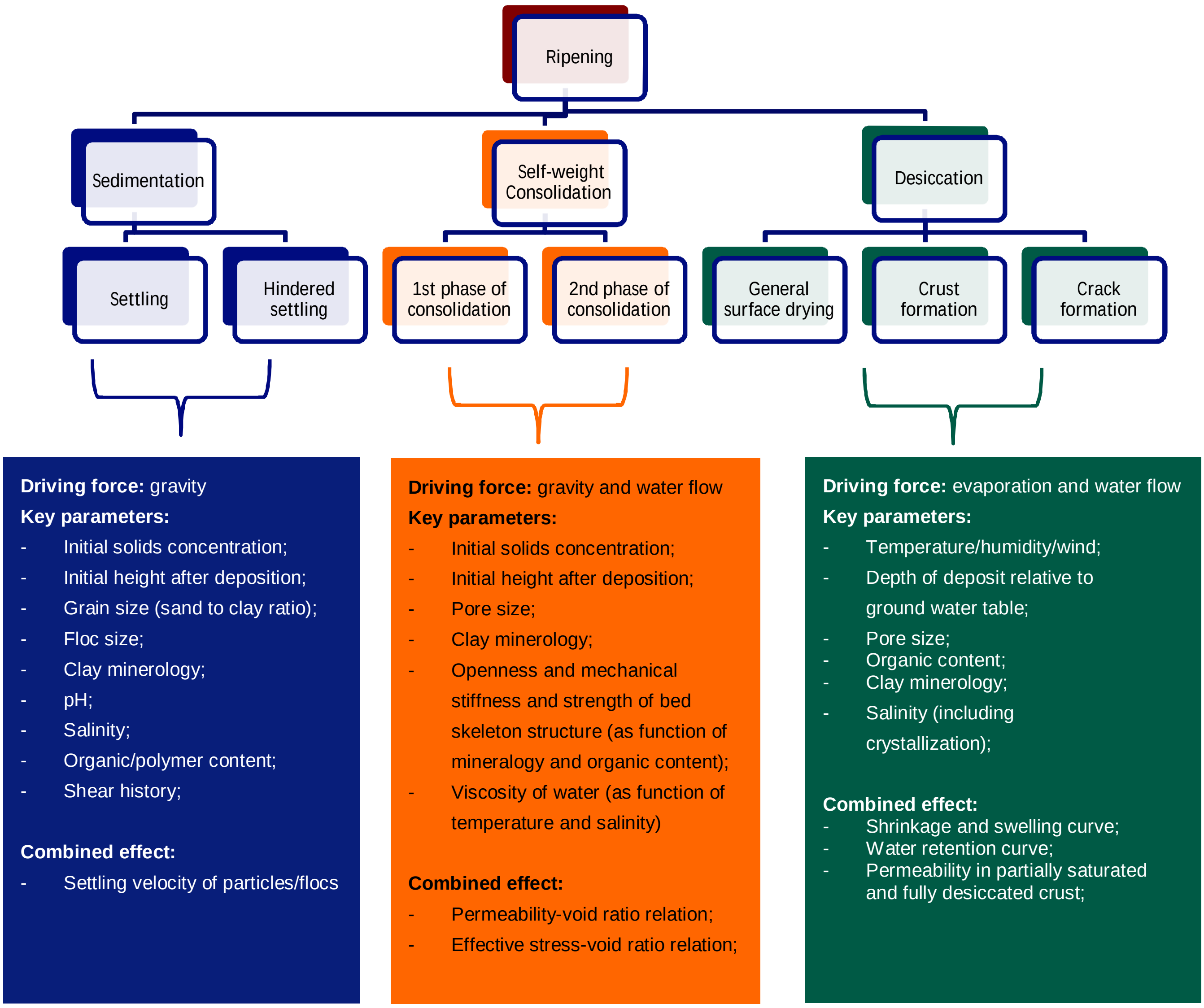

Figure 4: A summary of governing processes during ripening process.

3 Settling and self-weight consolidation

The soil formation process typically starts from a (dilute) suspension of particles in water. These are transported into the target area either naturally, by hydrodynamic forces, or artificially through pipeline transport. In the latter case, we often refer to the suspension as a slurry. When conditions are sufficiently calm, the suspended particles will form a deposit.

Depending on the initial concentration of solids, the mud goes through settling and consolidation or only consolidation. The transition between settling and consolidation lies at the gelling concentration (C_{gel}), at which the particles in suspension form a space-filling network (i.e., a gel). When the concentration of solids is larger than the gelling concentration, no settling takes place.

3.1 Definition of settling and consolidation

For a dilute muddy suspension in still water, the following sub-phases can generally be expected (Merckelbach, 2000; Winterwerp and van Kesteren, 2004; Hendriks, 2016). We assume that initially, in which floc aggregates and particles (e.g. fine sands) can easily move:

- Settling and hindered settling phase: the rapid downward movement of flocs/particles due to gravity by which a clear interface between mud and overlaying water will be formed is a typical signature of settling (also known as sedimentation). Settling occurs within the first few minutes to hours during which generally a significant amount of water is expelled to the surface. Settling occurs at very low solid volume concentrations (Φ_s< 0.1) where the settling velocity of individual particle is governed by gravity. At higher solids volume concentration (Φ_s> 0.3) due to interaction of neighboring flocs/particles and formation of water backflow, the settling velocity of individual floc/particle hinders (decreases). This is the hindered settling regime. The higher the concentration of solids in a suspension, the lower the settling velocity of particles. In this phase, the lowering in mud-water interface occurs with a lower speed than in the settling phase. Hindered settling occurs within the first 12 to 24 hours after deposition, during which a decent amount of water (up to 40% depending on the initial solids concentration) is expelled to the surface of deposit.

- Gelling point: the end of the hindered settling phase is characterized by the gelling concentration (C_{gel}) at which a space filling network ("skeleton") develops. At this point in time, all flocs/particles are considered in contact with each other leaving no possibility for further settling. The gelling concentration is defined as the solid concentration at which the bed begins to exist, known as the transition from hindered settling to the first phase of consolidation. In Figure 2, this is indicated with the dashed black line. When there is no longer a suspension (indicated with the black dot), the entire deposit solely experiences 1st phase consolidation (light brown).

- First phase of consolidation: starts after the gelling concentration is achieved. In this case, the lowering of mud-water interface (dewatering) is mainly governed by permeability and dewatering is much slower than in the (hindered) settling phase. The transition between these two phases can be recognized from the sudden change in slope of the mud interface. The first consolidation phase occurs within the first few days, up to a week. In this phase, the most important relationship to describe the dewatering process is the relation between void ratio and permeability. Note, during the first phase of consolidation generally the mud deposit is still in fully saturated condition.

- Second phase of consolidation: after the first phase of consolidation is completed, the second phase of consolidation starts, where deformation (e.g. reduction in mud-water interface) are even smaller than of the first phase of consolidation. In this phase, effective stresses dominate the consolidation process. The most important relationship to describe the dewatering process is the relation between void ratio and effective stress. During the second phase of consolidation the mud deposit is generally still in fully saturated condition. This phase may last for months to a year, the dewatering process is remarkable slow in this phase. If the water on top of the deposit is drained, the upper part of the deposit already enters the desiccation phase. This phase is explained in the following section.

3.2 Driving force and key parameters during settling and consolidation

The driving force behind settling and self-weight consolidation is gravity. During the (hindered) settling phase, the gravity descends flocs and solid particles downwards. This results in upward flow of water. In this phase, Brownian motion and friction between solids act as counter force. During the consolidation phase, gravity induces a gradient in excess pore pressure. This drives pore water flow, transporting water out of the deposit.

The key parameters affecting the settling behaviour of mud deposit, amongst many, are: concentration of solids, specific gravity of solids, grain size distribution, sand-to-fines ratio, clay mineralogy, floc size and density, presence of organic content and/or polymer, salinity, pH, and temperature. Some of these parameters (e.g. clay mineralogy, flocs size and density, salinity and pH) are interdependent, meaning that change in one may alter other(s) and as a result the settling behaviour of mud. These relations are comprehensively described in Dankers (2006), Mietta et al. (2009), Hendriks (2016), Chassagne (2021).

In the first phase of consolidation, under the effect of self-weight (i.e. total stress) and in absence of bottom drainage, while pores in the mud deposit are fully saturated, water will be squeezed out of deeper layers in the deposit and transported upwards to the surface via the microscopic channels in mud skeleton (network of grains and flocs). In this phase, the total weight above a given point in the mud deposit is mainly carried by water in pores. Hence, its consolidation behaviour depends on the permeability of the deposit (i.e. the ability to transmit water). The permeability of a deposit is directly proportional to:

- the square root of the particle size (Hazen, 1982); the coarser the grains/flocs the larger the permeability.
- percentage of very fine particles; as they may clog the connection between pores and the microscopic channels that allow flow of water;
- square root of void ratio (e); the larger the void ratio the larger the permeability;

For a given mud type, particle (floc) size and void ratio may differ as a function of shear history. This also affects the properties of a deposited mud: these depend on the cumulative dissipated energy per unit volume of mud prior to deposition. An example of such a property is the relationship between void ratio and permeability, which is often used as input for consolidation modelling. However, this property is non-unique for a given mud type, but also depends on the shear history.

In the second phase of consolidation, the load of the total weight above a given point in the deposit is gradually transferred from water to the mud skeleton. This transfer from pore water to skeleton introduces stress between grains in the skeleton which is called effective stress. Due to the gradual increase in effective stress, solid particles rearrange. This results in small deformation of the deposit, also driving out water. In this phase, the rigidity/compressibility of skeleton is an important factor. Like the void ratio-permeability relation, the effective stress-void ratio relation in a given mud type may be non-unique, depending on the shear and stress history of the mud.

4 Desiccation

4.1 Definition of desiccation

For a consolidating deposit, desiccation (i.e., drying) commences when overlying water is drained and the top layer of the deposit is exposed to the air (Figure 2). Water in the top layer starts to evaporate due to atmospheric influences (Figure 5). This results in an evaporation flux into the overlying air right above the deposit surface. If the evaporation flux in the top layer exceeds the flux of pore water from deeper layers of the deposit towards the surface (due to ongoing self-weight consolidation in deeper layers), the top layer starts to desiccate. Generally, desiccation starts from the surface and propagates downwards to deeper layers in a deposit. If bottom drainage pipes with good ventilation are used, desiccation may also occur at the bottom of a deposit.

Desiccation can be categorized into three main sub-phases (Sijbrandij, 2017):

- general surface drying
- crust formation
- crack formation

These sub-phases are elaborated in the following sections. Crust and crack formation are the two main signatures of the desiccation phase. Expansive soils (i.e. muddy soils) tend to change their volume, i.e. shrink and swell, in relation to variation in their water content. They shrink during desiccation within a dry period and swell during precipitation within a wet period. The time scale of these processes lies in the order of few days to a week. The volumetric change of the deposit due to water loss is crucial for the initiation and propagation of crust and cracks.

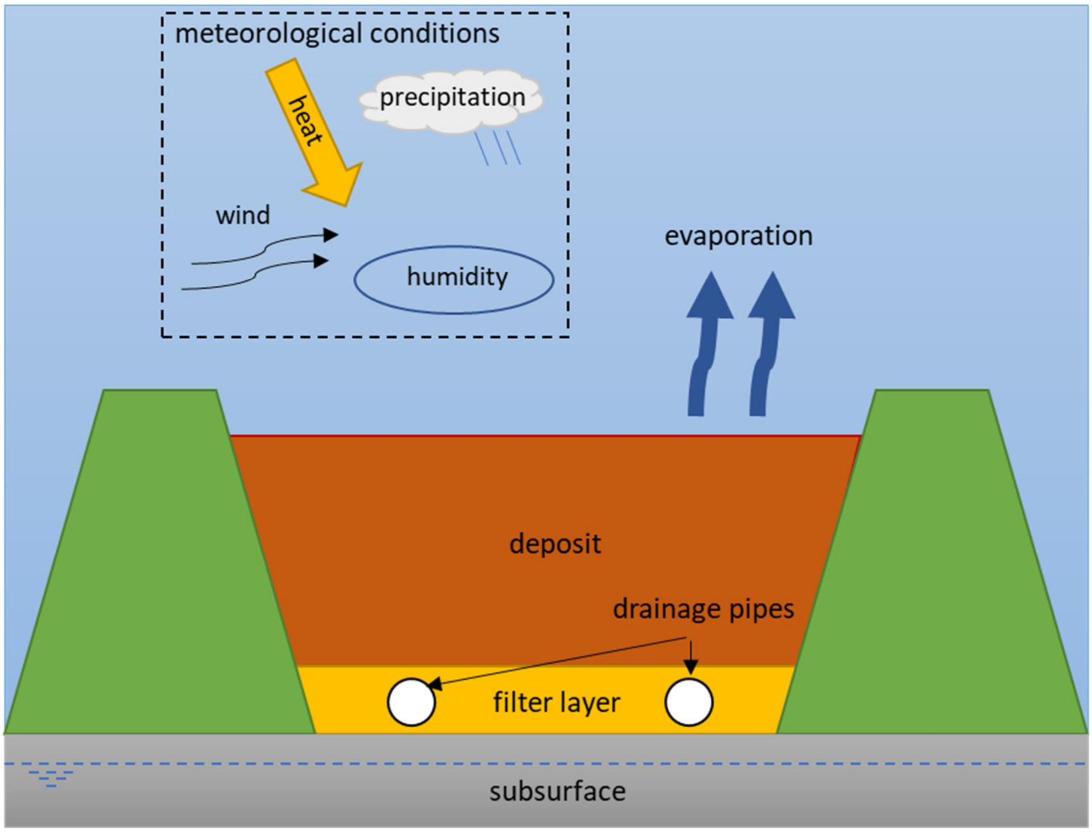

Figure 5: Conceptual sketch of desiccation phase. Top part of deposit is not (fully) saturated, air can penetrate deposit. Water evaporates from top layer, rate at which this happens depends on climatic conditions and properties of deposit.

The causal relationship between water loss and shrinkage is described in literature. Some researchers (e.g. Morris et al.,1992) believe that water loss engenders a significant volume contraction in the structure of active clay minerals in the soil, e.g. montmorillonite, resulting in shrinkage. Such clays are also known as the plastic clays with a larger effective cohesion and a larger tensile strength compared to the lean clays (Baker, 1981). Others (e.g. Tang et al., 2010) relate the moisture loss to development of capillary suction and as a result rearrangement of soil particles towards a successively closer arrangements of soil fabric. They argue that when surface of an initially saturated soil is exposed to atmosphere, air–water meniscus begins to form and as a result capillary suction. This capillary suction rearranges the soil particles and causes volume reduction in soil structure. There is of course a limit to rearrangement of soil particles. When this limit is reached, with further water loss, no more volume reduction occurs. Factors such as temperature, relative humidity, wind, layer thickness and boundary conditions also influence the volumetric change in a soil type (Mishra et al., 2008).

4.2 Driving force and key parameters during desiccation

The driving force behind desiccation is surface evaporation. The desiccation behaviour of a muddy deposit is a function of both its own material properties and the climatic conditions. Relevant material properties are mineral composition, clay content and layer thickness, whereas relevant climatic conditions are temperature, relative humidity, wind and precipitation (Mishra et al., 2008).

The water flux from the mud deposit by evaporation cannot exceed the potential evaporation governed by the climate. It will be close or equal to this limit if two conditions are met:

- the surface drainage is enough, as evaporation of water overlying the deposit surface won't extract any water from the soil;
- the soil exposed to air is sufficiently moist, as the evaporation rate decreases with decreasing soil moisture content.

When the desiccation process continues for a period of several days to weeks, depending on the initial moisture and climatic conditions, the pores start to desaturate. Air can then enter, which results in development of negative excess pore pressures. This is known as matric suction. Matric suction in the surface layer enhances the pore pressure gradient in deeper layers of the deposit, which causes water to flow upwards to the surface. The larger the matric suction the more profound the flux of water. Note, there are limiting factors that limit the effect of matric suction (such as crust formation), which will be discussed later (Section 4.3.3).
Furthermore, the penetration of air into the deposit leads to oxidation of the soil. This triggers several (bio-) geochemical processes. The growth of plants and bioturbation by animals can also significantly influence desiccation. We will discuss these different influences separately. Explaining the effect and contribution of all parameters mentioned above cannot be properly done within the limited scope of this study. However, we will try to cover the effect of the main parameters and the most important interactions between them.

The flow of water out of the deposit is shown in Figure XX. There are

4.3 The three subphases in the desiccation process and their key parameters

4.3.1 General surface drying

General surface drying occurs while the pores at the surface remain fully saturated. In this sub-phase, water evaporates from the top of the surface at a higher rate than water is supplied from deeper layers in the deposit. Hence, the water content in the top layer of the deposit decreases. During this process the pores at the deposit surface are saturated with a water content close to the Liquid Limit (Haliburton, 1978). Due to the flux of water out of the deposit, minor shrinkage occurs. However, this is not sufficient to evoke significant crust or crack formation.

Generally, this sub-phase lasts relatively very short (in the order of a day to a few days) and its influence is less significant compared to other desiccation sub-phases. The duration of this phase is governed by meteorological conditions and the initial moisture of the deposit. The latter means how far the deposit has consolidated before its surface is exposed to the atmosphere.

4.3.2 Crust formation

Crust formation hampers the flux of water out of the deposit. The mechanism of crust formation and its development are explained here. Crust formation is defined as an extreme volume reduction in a soil layer which results in contraction between grains and very small pores. Due to evaporation, the water content at the surface decreases, which leads to shrinkage. This way, a thin crust forms, which then gradually thickens. The capillarity and permeability of a muddy crust is close to zero (Haliburton, 1978). This negatively affects the desiccation of deeper layers in the deposit, as less water from these layers can be transmitted upwards. This slows down the evaporation rate and retards further desiccation of deeper layers. The thicker the crust, the more profound its negative impact on desiccation of the entire deposit.

Stark et al., 2005b reported that the crust may impose additional surcharge load on the saturated soil/mud deposit underneath. This is because solid particles in a crusted layer are not buoyant which results in an increase in effective weight of the top layer. This additional “overburden” may evoke further consolidation and thus dewatering from deeper layers in the deposit (Sijbrandij, 2017). A crust also hampers water infiltration into soil (e.g. for salt removal practice by means of rainfall run off and irrigation). As a rule of thumb, the water infiltration is proportional to the fourth power of the diameter of the pores, hence crust formation strongly reduces the water infiltration into soil/mud (Duley, 1939).

Summarizing, crust formation and development mitigates the desiccation from deeper layers in a muddy deposit. It also significantly reduces the infiltration. If conditions are favourable, a crust may form within several weeks. The effect of crust formation on the temporal development of the deposit may last much longer: up to years. Its effect also increases with time as the crust thickness increases.

4.3.3 Crack formation

Crack formation promotes the flux of water out of the deposit. This is simply because cracks expose a larger surface area to the atmosphere. The mechanism of crack formation and its development are explained here. Cracks result from shrinkage while the crust is being formed. As mentioned, desiccation usually starts from the deposit surface and gradually migrates towards deeper layers. This means that at a given point in time the surface layer has shrunk more than the deeper soil layers. This shrinkage gradient along the depth leads to tensile stress (Tang et al., 2010). Additionally, heterogeneity in the deposit may lead to larger (local) shrinkage gradients, and thus further increase the tensile stress in the deposit (Nahlawi and Kodikara, 2006). Cracks are initiated when the tensile stress exceeds the soil tensile strength (Corte and Higashi,1960). These cracks are likely initiated at soil surface defects and flaws, such as older cracks, larger pores, trapped air bubbles and large grains (Kodikara and Costa, 2013). This is simply because the tensile strength of the soil at these points is usually low (Nahlawi and Kodikara, 2006). Figure 5 shows schematic view of crack development in soil along the depth of deposit with time (structure state development).

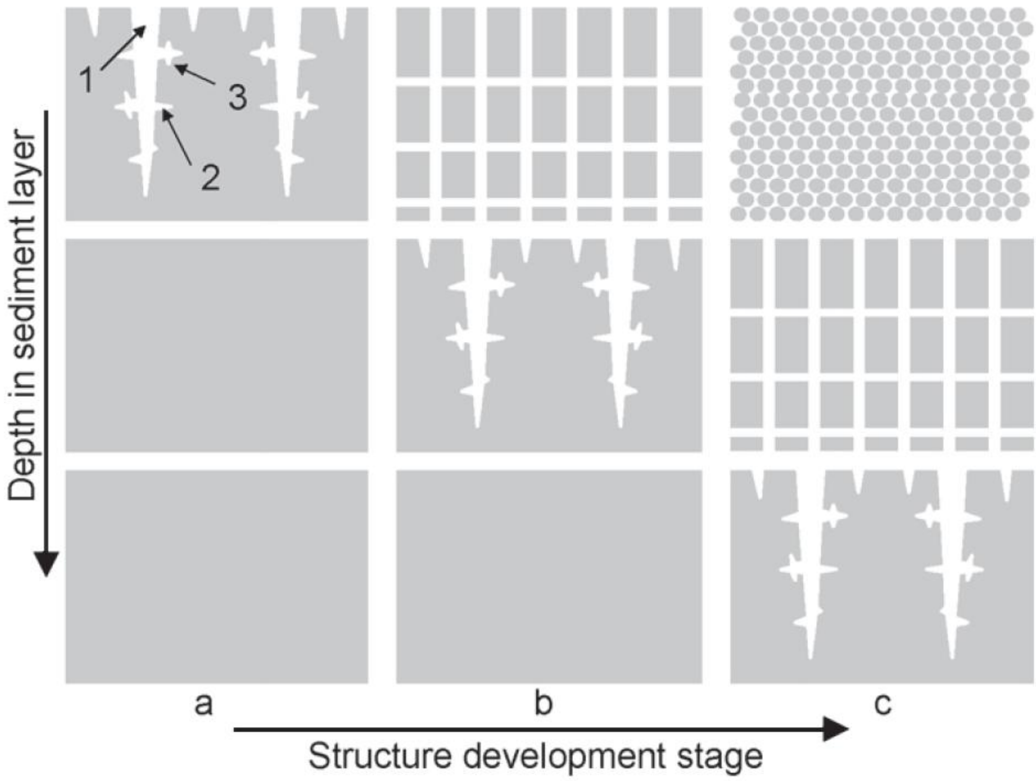

Fig. 2.2: Schematic cross section of a layer of dredged material at different, stages of structure development (After Baver et al. 1972, Dexter, 1988 and, Vervoort et al. 1999). a = very coarse prismatic structure with primary (1), secondary (2), and tertiary cracks (3); b = coarse blocky and platy aggregates on very coarse prismatic structure; c = medium and fine aggregates on coarse blocky and platy aggregates and very coarse prismatic structure

Figure 6: Crack development in soil along the depth of deposit with time (structure state development), from Talmon and Luijendijk (2019).

Matric suction declines (nonlinearly) with depth from a peak matric suction at the soil surface to zero matric suction at the water table in a soil deposit. On top of the matric suction, solute (osmotic) suction should be added depending on the salt concentration in the pore water (Morris et al., 1992). The solute (osmotic) suction reaches its peak just below the water table. Within a crack, variations in the matric suction occur much more rapidly than changes in solute (osmotic) suction. Matric suction has a greater effect on cracking than solute (osmotic) suction within the usual time frame of engineering interests (Morris et al., 1992).

Matric suction may produce two contrasting effects. On the one hand, as explained above, by generating a shrinkage gradient along the depth, it increases the tensile stress resulting in initiation and propagation of vertical cracks below horizontal drying surfaces (Morris et al., 1992) This tensile stress is increasing when water evaporation proceeds (Tang et al., 2010). On the other hand, soil tensile strength increases with matric suction, as matric suction increases the effective stress between grains, providing increased resistance to crack formation (Morris et al., 1992; Zeh and Witt, 2007) thanks to rearrangement of particles forming a stronger/denser soil fabric.

A cracked soil has a much higher permeability than the same soil at the same water content but in an intact state. However, this effect can be masked (or even reversed) by low hydraulic conductivity in regions of desiccated soil between cracks (Blake et al. 1973) and in the zone of shrinkage ahead of the crack tips.

In case of a saline soil, crack depth may be smaller. This is because of deposition of high salt concentrations in the desaturated zone close to the soil surface. Deposition of salts in the interparticle contact zones increases the tensile strength of the soil which counteracts crack development (Morris et al., 1992).

Though no research has been performed to assess the effect of temperature on the formation of cracks, it may also be relevant. Shear strength decreases with temperature (Cui et al., 2000); which suggests that tensile strength should also decrease with temperature. Kayyal (1995) found out that suction rate increases with evaporation rate. Thus, at a higher temperature, higher suction rates can be expected. As a result, the induced surface tensile stress can exceed the tensile strength of grains in a shorter time. This implies at higher temperature; desiccation cracks initiate faster in the surface layer.

The presence of organic matter (20–30% total dry weight) enhances the shrinkage resistance and shear strength. High organic content soils can generally hold more water resulting in a larger linear shrinkage strain (Puppala et al., 2007). This implies that organic content may act as a mitigating factor against the drying process.

4.4 Climatic conditions

Relevant climatic conditions are temperature, relative humidity, wind and precipitation (Mishra et al., 2008). Temperature and humidity are essential here, and should be considered together. An increase in temperature results in higher motion velocity and kinetic energy of water molecules and lower viscosity and interfacial tension of water (Tang and Cui, 2005). This increases the evaporation rate from the soil surface only if the relative humidity is low. For instance, field surveys show that high temperatures during wet seasons do not produce wide, deep cracks (Morris et al., 1992).

Air temperature has a direct relationship with humidity: the higher the temperature the lower the relative humidity of the air, hence further rise in the evaporation rate (Tang et al., 2010). However, as drying progresses, the water evaporation rate decreases and finally reaches zero. There are three underlying reasons for this: (i) the availability of water in soil decreases with time; (ii) the developed high matric suction bounded the water molecules and prevented them from escaping to the atmosphere; and (iii) the vapor pressure gradient across soil–air interface decreases with drying (Wilson et al.,1997; Tang et al., 2010).

4.5 Biological processes

Biological processes in ripening play on different scales. In this section, we solely focus on the role of macroscopic flora and fauna, such as worms and vegetation.

Worms can be introduced into a deposit by birds bringing cocoons attached to their claws or by horizontal dispersion (4-10m per year) (Bal, 1982). Worms burrow through the top layer of a deposit. The resulting tunnels are important pathways for water to flow through during consolidation and desiccation (Huang et al. 2007). Worms rework 5-120 tons of soil per hectare (Bal, 1982). Furthermore, worms also consume organic matter which may help in achieving project requirements.

Worms prefer moist conditions but can also crack dry soils with tensile stresses. They can survive in anoxic environments and can therefore contribute during the early stages of self-weight consolidation (de Lucas Pardo, 2014), but also later in the ripening process (Vermeulen et al. 2003). Certain species like *Tubifex tubifex* have a high tolerance for reduced oxygen conditions (Chapman, 2001) and survive in severely polluted environments where almost no other species can endure (Engle et al., 1994). Because of their ability to withstand extreme conditions, *Tubifex* worms are currently being applied in pilots for the dewatering and ripening of oil sands tailings (Yang et al., 2016, de Lucas Pardo et al. 2021).

Plants directly interact with the physical and chemical components of a deposit through their roots (Angers and Caron, 1998). Plant roots enhance the effective drainage and hydraulic conductivity of the deposit (Angers and Caron, 1998; Kodešová et al., 2006; Gerke and Kuchenbuch, 2007). The hydraulic conductivity of the deposit is enhanced by root-growth induced cracks, forming macropores and drainage channels (Barciela Rial, 2019). Additionally, some vascular wetland plants provide oxygen to the soil via transport of oxygen to the root system and its surroundings (the rhizosphere) (Trapp & Karlson, 2001). Though drainage of a vegetated deposit increases, this does not necessarily lead to increased consolidation rates. A competing effect is the strengthening of the deposit by roots, i.e. armouring. If the latter effect wins, consolidation rates may even be retarded as compared to a bare deposit (Barciela Rial, 2019).

4.6 (Bio-) Geochemical ripening

After deposition of freshly dredged sediment, the sediment conditions will remain anoxic and reduced for a while. Crack and aggregate formation due to physical ripening improve oxygen penetration into the deposit. Hence, larger parts of the deposit will be subjected to oxygen. Parts of the deposit in contact with oxygen will immediately undergo chemical and biological ripening: reduced components will be oxidized both biologically (through microorganisms) and chemically, the redox potential increases (matter of a few months, Vermeulen et al. 2007), the ionic composition and concentration of the soil solution will change, less stable minerals will weather and ratios of adsorbed ions will change.

The main function of microorganisms in the biological ripening process is to degrade soil organic carbon into humus, which is faster during aerobic conditions compared with anaerobic conditions (Rijtema et al., 1999). Microorganisms also affect both the nitrogen cycle and sulfur cycle and thus contribute to chemical ripening. Despite the oxygen conditions (aerobic/anaerobic) microorganisms continue to be active and can thereby affect the system drastically. For example, in sulfate rich sediments anaerobic bacteria can transform sulfate into the toxic hydrogen sulfide (H_2S), which will inhibit activities of other microbial processes.

In ripening of sediment, the oxidation of the reduced sulfur components (FeS, FeS_2, $Fe(OH)_3$ and H_2SO_4) is considered most important, because of the formation of sulfuric acid. If the sediment is poorly buffered, i.e., in absence of CaCO3, this may lead to a strong decrease in pH (Ritsema et al., 2000).Subsequently, this may lead to mobilization of heavy metals (Calmano, Hong, & Förstner, 1993). This is important for the ripening process as in some cases mobility of certain ions is not always wanted because of ecological constraints. In order to avoid leachate flowing into restricted areas, a project manager should know in which chemical ripening state the sediment is.

The increase in aeration of a soil is best monitored by the redox potential (E_h), which increases upon increased oxygen availability. When the redox potential increases, more and more reduced substrates in the soil are oxidized. Many of these chemical processes are biologically catalyzed. The result of chemical ripening is also visible in the field, where the black colored, reduced materials in the sediment turn into brownish or yellowish gray colors. . The oxidation of FeS to $Fe(OH)_3$ causes this change in color.

Oxidation of reduced compounds follows a sequence of:

reduced organic matter → CO_2
S^{2-} → SO_4^{2-}
Fe(II) → Fe(III)
NH_4^+ → NO_2^- & NO_3^-
Mn(II) → Mn(IV)

When a deposit dries out completely, both chemical and microbiological processes will cease. Hence, optimal conditions for aerobic processes are expected when the deposit is not completely dry but most pores become filled with air (Vermeulen et al. 2003).

5 Main take-aways from literature review

The main take-aways from this literature review are listed below. These can provide guidance for later stages of the Living Lab for Mud project and the development of practical design rules.

- Physical ripening process of a mud is defined as transforming the mud into a suitable soil for a specific application.

- The criteria to judge if a soil is ripened or not depend on the engineering application that soil is going to be used. Design requirements may differ per project.

- The terms “ripening” and “desiccation” are not exchangeable. Ripening includes the entire transformation process from fresh mud to suitable soil for a given application. While desiccation (i.e. drying) refers to removal of water from a deposit under the influence of evaporation.

- Mud undergoes three main phases while transforming into soil namely: (hindered) settling, consolidation and desiccation.

- The driving force for (hindered) settling and consolidation is gravity.

- The time scale of (hindered) settling is in the order of 12 to 24 hr during which roughly speaking up to 25% (rough number) of water can be expected to be expelled from the deposit. The (hindered) settling occur only in case of highly diluted suspensions.

- Consolidation is classified into first phase (governed by permeability) and second phase (governed by effective stress development) of consolidation.

- The time scale of the first phase of consolidation is in the order of a few days to a week during which roughly speaking up to 10% of water can be expected to be removed.

- The time scale of the second phase of consolidation is in the order of several months to years during which gradually water will be expelled from the deposit.

- The driving force for desiccation (i.e. drying) is evaporation through formation of matric suction as a result pore pressure gradient along the depth of deposit.

- Two main features of desiccation are crack and crust.

- Cracks motivates dewatering by introducing larger soil surface area.

- The time scale of crack formation is in theory infinite. The depth of crack however is limited mostly up to the ground water table.

- Crust mitigates dewatering by reducing capillarity and permeability of crusted layer. The time scale of crust formation is in theory infinite. The depth of crust is mostly limited by the depth crack.

- Formation of crust introduces surcharge on the non-crusted deposit below the crusted layer. This may evoke further consolidation of the deeper layers in the deposit. The water flux induced by this effect most likely expelled from the side cracks.

- At the onset of the ripening process (just after surface runoff) the evaporation flux is completely governed by weather conditions, but as the soil moisture decreases transport within the soil becomes a limiting factor and both evaporation and internal transport govern the water flux out of the soil. In the end, when the moisture content of the soil surface becomes very low, the water flux is completely governed by internal transport.

- Heat in combination with low humidity encourages crack formation.

- Organic content mitigates crack formation and development.

- Salt mitigates crack formation and development.

To a certain extent, drainage and the exposure of moist soil to air is taken care of by itself via crack formation, but this process may be enhanced, e.g. by:

- bottom drainage and ditches to enhance dewatering
- reworking/ploughing by exposing wet soil to atmosphere
- making heaps to increase the soil surface area
- vegetation

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