The impact of climate change on soil ageing processes in levees

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2020/06/05

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Photos: Ommelanderzeedijk under construction (Waterschap Noorderzijlvest, 2018).

Acknowledgements

To start, we would like to express our acknowledgement to our commissioners Martin van der Meer and Arjan Kooij. They made this project possible, gave us clear instructions and insights, and steered us into the right direction in the beginning of this project.

We would also like to express our acknowledgement to our supervisor, Jantsje van Loon-Steensma, for her advice, motivation, enthusiasm, comforting conversations, and guidance throughout this project.

Lastly, we would like to thank Martine van der Ploeg, Marcel Hoosbeek, Henk van Hemert, Jan Willem Nieuwenhuis, Robbert Bruin, Renée Rookus, and Richard Marijnissen for their time, opinions, insights, and enthusiasm which contributed to this report.

Disclaimer

Contents

Executive summary

The Netherlands has a long history in flood protection by building levees. However, climate change might form a risk for the strength of the levees. This challenge is becoming increasingly difficult as sea levels are rising, summer droughts are getting more severe and precipitation patterns are likely to change. These climate change induced phenomena have shown to influence the strength of levees. In order to cope with climate change, levees should be strengthened effectively in the future. POV Dijkversterking van Gebiedseigen Grond (POV-DGG) is working on this topic. Currently, there is a gap in knowledge on how soil ageing processes influence levee strength. As climate change might speed up or intensify soil processes, it is important to shed light on this topic. This has been studied by means of literature research and expert interviews. This report aims to identify (1) how levees are typically structured (2) which processes influence the strength of soils, (3) what the projected climate change is for the year 2050 and combines this knowledge to predict the influence of climate change on levee stability.

Levee structure
Levees are structured in roughly two different ways: an impermeable core (e.g clay, concrete) surrounded by permeable material (e.g. sand or earth-fill) to strengthen the structure, or an impermeable mask over permeable filling material. The Grebbedijk is an example of a levee with an impermeable clay core, while the Ommelanderzeedijk is a levee that consists of a sand core overlain by an impermeable clay.

Soil ageing processes in levees
The studied soil processes are erosion, shrinking and swelling, salinization, soil-vegetation interactions, and organic matter influence. The higher the fraction of very small grains of a soil, the higher the resistance to erosion, especially when the water content is high. However, the resistance to erosion of coarse-grained soils (>0.3mm) increases with increasing diameter and decreases with higher water content. Shrinking is the result of soil desiccation, and conversely, swelling occurs when water molecules enter the inter-plane spaces of clay minerals. Shrinking can cause cracks in soils and swelling can cause heaving and uplifting. The extent to which shrinking and swelling occurs is proportional to the clay content in the soil and requires a minimum of 17%.
Shrinking and swelling in clays can also be induced by soil salinization, which is a process in which salt is introduced into the pore fluid. Salt ions can replace particles between two clay sheets. When replacing water molecules, shrinking occurs. When replacing smaller ions, swelling occurs. Salinization could lead to dispersion of clays when the space between two mineral sheets increases to the extent that the clay loses its structural integrity. Vegetation plays a vital role in soil resistance to erosion, by binding together the top layer of the soil. In order for vegetation to grow, three factors should be met in sufficient quantities: pore space, water and nutrients. Organic matter in soils can modify shrinking behaviour of soils by interacting with clay and salt. It can also make coarse-grained soil water repellent. Oxidation of organic material could shrink levees irreversibly.

Climate change effects in the Netherlands
There are three components of climate change that could affect soil ageing processes in the Netherlands for the period between now and 2050. The average **surface temperature** will increase, more **extreme precipitation** and **droughts** will occur, and sea level will continue to rise. The studied soil ageing processes are all influenced by climate change, which could affect levee stability in different ways. Temperature increase will modify organic matter processes. Droughts are likely to increase soil shrinking and cracking, which could affect the impermeable layer and could later lead to piping, internal erosion, and slope instability. Moreover, droughts will cause withering of the vegetation cover and could increase salt water seepage, especially in combination with sea level rise. Extreme precipitation could lead to enhanced erosion and amplification of the soil moisture cycle. It also increases the phreatic line which could affect levee stability.

Vulnerability
In short, clay parts of levees are expected to be affected most by climate change and are mainly affected by droughts. For the Ommelanderzeedijk, this means that the clay mask and old clay embankment could be vulnerable to stability loss. As the Grebbedijk consists dominantly of clay, its structure is vulnerable to climate change.

Recommendations
As there still is a gap between the civil engineering knowledge and soil knowledge, cooperation between soil scientist and civil engineers could increase the efficiency of levee reinforcement projects. Research in the near future could focus more on bio-activity and the potential of lime treatment. Moreover, clay mineralogy could be added to the existing clay quality criteria. Also, a high variation in vegetation species is important. Collaboration with French levee engineers and soil expert could be of major importance, as they could provide information about how to cope with droughts and heat. Droughts will be a major problem for which more adaptation strategies need to be developed. The main focus towards the future should be on droughts regarding levee stability. Therefore, we propose further in-depth research to be conducted on the effects of increasing droughts on the four soil ageing processes in levees.

1. Introduction

1.1 Background

The Netherlands has a long history in flood protection by building levees. However, climate change might form a risk for the strength of the levees. In the coming decades, the Netherlands will increasingly face the challenge to adapt to climate change. One of the most important threats is the risk of levee collapse during extreme storm and surge events (Van Meurs & Kruse, 2017). This could lead to floods in large parts of the country. The last severe disaster occurred in 1953, where especially Zeeland and Zuid-Holland were impacted (Hage & de Poll, 2015). Since then, many adaptation measures have been taken to prevent recurrence.

The need for adaptation measures since 1953 has always been there, as a large proportion of the Netherlands is located below sea level and prone to flooding. The Delta Commission was assigned to ensure levee safety in the Netherlands. The National Flood Risk Analysis in the Netherlands (VNK) project has put the ideas of the Delta Commission into practice (Vergouwe, 2016). An integrated analysis for all flood defences in the Netherlands has been made. In order to ensure flood safety, the strong and weak points have been analysed and the flood and damage probability has been estimated thoroughly (Vergouwe, 2016).

Levees need to be adapted to the effects of climate change in the future. As a consequence, safety standards are increasing. Existing levees have to be maintained, tested and reconstructed to remain flood proof. The Dutch Flood Protection Programme (DFPP) of The Netherlands is assigned to improve flood protection structures up to the newly derived safety standards (Jorissen et al., 2016). Every 5 years the flood defences are tested according to the new safety standards. This determines if a levee is flood proof (Jorissen et al., 2016).

Climate change could have an impact on levees in different ways. Firstly, the sea level is continuously rising, which could cause problems regarding the levees (Le Bars et al., 2017). Secondly, droughts, extreme precipitation, and extreme river discharges can affect the stability of levees (Van Meurs & Kruse, 2017). Thirdly, different precipitation patterns and temperatures will change soil forming processes in the levees, which could affect the levee stability (Mitchell & Soga, 2005). Problems regarding climate change and levee stability already have been observed in recent years (Bruin & Rookus, pers. communication).

In order to cope with climate change, it is important to find strategies to strengthen Dutch levees effectively in the future. POV Dijkversterking met Gebiedseigen Grond (POV-DGG) is working with local soils on this topic. One of the challenges is to assess how processes in soils in levees change under the influence of climate change and how to change levee reinforcement measures based on these processes.

1.2 Research questions

The goal of this project is to present insights on the soil ageing processes in levees to the commissioners of POV Dijkversterking met Gebiedseigen Grond (POV-DGG). This information can be used for adaptation strategies regarding levee management in the Netherlands to ensure protection against floods, given the circumstances of climate change. The focus will be mainly on climate change induced soil ageing processes in levees. Therefore, the main research question is:

How will levees in the Netherlands be affected due to the effects of climate change on soil ageing processes?

In order to answer the main research question, the following sub-questions will be answered:

- What determines the soil ageing process in levees and what is the effect on levee stability?
- What is the projected climate change in the Netherlands for the year 2050?
- Which adaptation strategies could be applied to keep the levees stable and could local (i.e. Dutch) soils be used for these strategies?

1.3 Objective and scope

The construction and maintaining of levees usually contains civil engineering expertise. However, typical soil processes expertise is commonly not considered. Therefore, the commissioners of POV dijkversterking are aiming for the connection between the civil engineering expertise and the Wageningse soil expertise. The goal of this project is to present insights on the process of soil ageing in levees to the commissioners of ''POV Dijkversterking met Gebiedseigen Grond''. Subsequently, the results of the project will be shown in the form of a report, which will be delivered to both the supervisor of this project group and the commissioners. In order to present the main findings, the report will contain the following elements.

- Explanation of the effects of climate change on soil ageing processes in levees
- A clarifying table on the effects of climate change on different type of soils and their ageing processes
- Recommendations for effective adaptation strategies for levees in the Netherlands
- Summary of main findings

1.4 Methodology

This project has been carried out via literature review, complemented by interviews with expert and therefore contains both primary and secondary data (Walliman, 2017). Relevant literature are not only pieces about levees and levee construction in the Netherlands and elsewhere, but also about soil formation and degradation. For this report, climatological historical data of how the climate has changed in the Netherlands for the period 1951-1980 has been used. For possible future climate projections for the year 2050 in the Netherlands, the IPCC Representative Concentration Pathways (RCP) and literature studies have been used (Tank et al., 2014). With regard to sea-level rise, a study from Le Bars et al. (2017) has been used. The levees in the Netherlands need to be adapted to the worst possible scenarios, to prevent possible disasters. The worst-case scenario – RCP 8.5 – could be used for a future climate projection. It is therefore necessary to understand how soil ageing processes behave in countries where the climate currently is similar to worst case scenario in the Netherlands for 2050.

In this report, the ageing of soils in levees was studied. Soil ageing can be described as the time effects on strength and deformation of soil properties. This can be on both short and long term, but for this project only soil ageing processes that could change between now and 2050 are considered. Information about soil ageing processes has been gathered from both academic literature and governmental sources. Initial focus was on sun exposure, precipitation, temperature, biological activity, soil composition and heterogeneity. Relevant experts regarding those factors include civil engineers and soil scientists. Information from the interviews has also been used in order to determine which soil processes are most important regarding climate change and levees. In total, 6 interviews have been conducted. To prepare the interviews, thematic and relevant questionnaires have been compiled. Both the questionnaires and interviews can be found in the appendix.

The report aims to determine the impact of climate change on the soil ageing processes. Information on the change of environmental factors have been gained by looking at data produced by climate models for the Netherlands. After that, the report aims to examine ways on how the ageing process can be influenced during or after the construction of a levee to make it more resilient towards the future. Finally, this information has been used to formulate an advice in order to make levees more future resilient.

1.5 Reader's guide to contents

Chapter 2 of this report focuses on the levee structure and levee vulnerabilities and will elucidate on two levees in the Netherlands: The Ommelanderzeedijk in Groningen and the Grebbedijk in Utrecht and Gelderland. Chapter 3 contains an overview of relevant soil processes and properties in general and in levees as these processes could be affected by climate change. Chapter 4 focuses on how the climate in the Netherlands will change for the year 2050. It focusses on climate scenarios published by the KNMI. Chapter 5 gives an overview of how changes in climate could affect the soil processes described in chapter 3. It contains an overview of how these processes could affect levee stability. The focus will be on the Grebbedijk and Ommelanderzeedijk. Ultimately, chapter 6 consists of the conclusions and recommendations resulting from this report

2. Levee structure

2.1 General structure

Levees are built to protect the hinterland. Therefore, they have to be adapted to the most severe circumstances, such as high water levels and strong waves. Each levee compartment has its own function. An overview of possible levee compartments is shown in figure 1 and most relevant ones are discussed in this chapter. Each compartment has a different function and different properties.

Earthfills
Earthfills are the main volumetric component of most levees (Van Hemert et al., 2013). They consist out of granular or cohesive materials like clay, silt and sand (Van Hemert et al., 2013). Mostly, this material is obtained from local soils. Therefore, there is not one type of earthfill. Most earthfills in Dutch levees have evolved over history and consists out of several layers. These are mostly locally available soils. The primary function is to provide mass stability against water pressure.Moreover, it has to be impermeable and resistant against erosion. Based on the quality of earthfill material, other levee components will be selected. The steeper the slope, the smaller the area and the lower the levee stability.

Earthfill construction is based on:

- Minimum levee height
- Available space
- Properties of available material
- External forces.

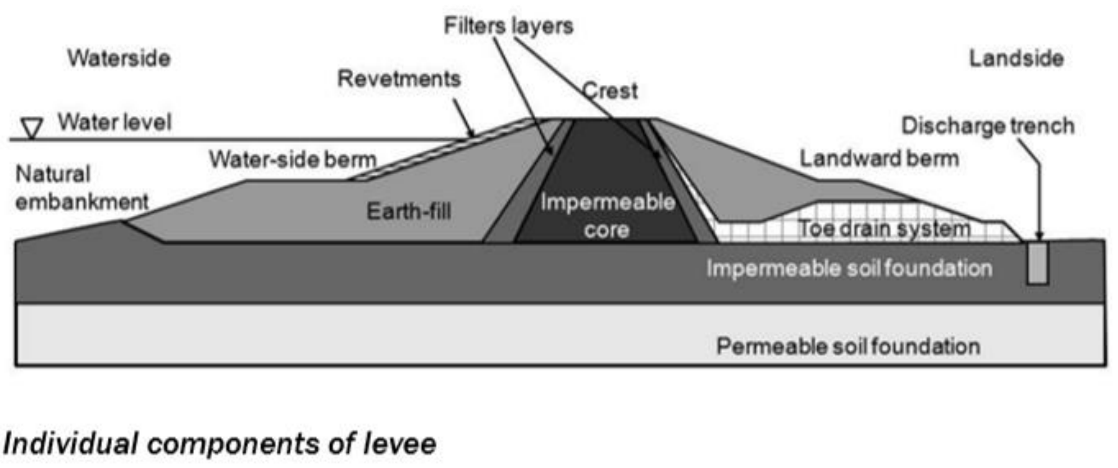
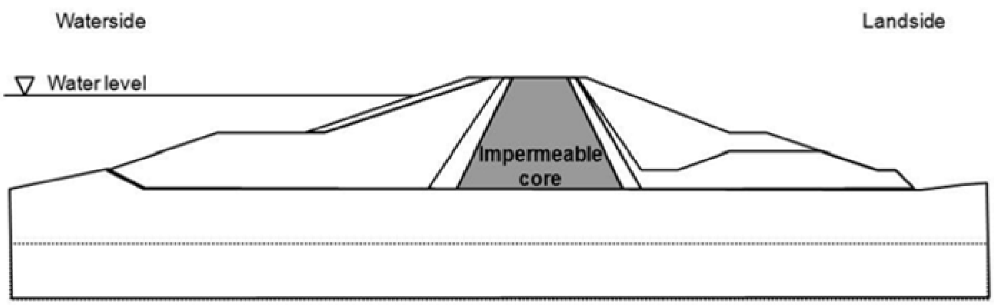


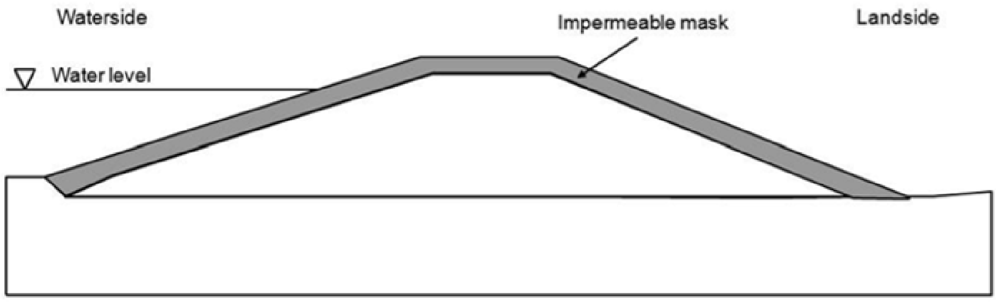
Figure 1: General overview of levee compartments. The earthfill is the most important component (van Hemert et al., 2013).

Impermeable cores and masks
When earthfills are not sufficiently impermeable, extra levee components are needed. Often impermeable cores or impermeable masks are used to make levees more impermeable, as shown in figure 2. Masks also promote erosion protection (Van Hemert et al., 2013).

The goal of an impermeable core is only to retain water temporarily during flood events. For that, absolute impermeability is not needed. Often clay is used in the core (Van Hemert et al., 2013). However, cracking may occur and form a risk in case of changing wet and dry conditions. This is more frequent in the masks than in the cores (where it is also difficult to investigate the mechanism). An impermeable mask is a revetment type.



Impermeable core



Impermeable mask

Figure 2: When the earthfill is not permeable enough, an impermeable core (above) and/or a impermeable mask (below) could be applied (van Hemert et al., 2013)

Revetments
Revetments are the upper layers of levees that are directly exposed to external forces. They have different functions on the waterside than on the landside. On the waterside, most important function is protection against external erosion (Van Hemert et al., 2013). On the landside, the main function is protection against surface runoff, eventually due to overtopping/overflowing (Van Hemert et al., 2013). Revetments typically consists of grass, rip-rap, asphalt or other materials. The role of vegetation in revetments is discussed in chapter 3.5.

2.2 Ommelanderzeedijk

The Ommelanderzeedijk is a coastal clay levee that protects the province of Groningen from floods (Figure 4). The levee is located between Delfzijl and Eemshaven and has a length of almost 12 kilometres. The difference between the Ommelanderzeedijk and other coastal levees is that the Ommelanderzeedijk is also earthquake proof since 2013. The province of Groningen occasionally experiences earthquakes due to the extraction of natural gas. Therefore, the Ommelanderzeedijk is constructed in a way it can cope with earthquakes with a magnitude level of 5.0 on the scale of Richter (Noorderzijlvest, 2020).

The original Ommelanderzeedijk – before 2013 – consisted of an old clay levee on the water side berm and a sandy core and earthfill on the landward berm. The impermeable layer on top of the levee consisted of clay as well. On the water side, stones of 20 x 20 centimetre from Norway have been added to the construction (Nieuwenhuizen, pers. communication). The levee has a height of almost 8 metres and the width of the levee construction is approximately 70 metres (Bos et al., 2013). Figure 3 depicts a schematic overview of the Ommelanderzeedijk. A recent storm – the Sinterklaasstorm in 2013 – has been added to the figure in order to show how high the sea level can get during a storm (Waterschap Noorderzijlvest, 2018).

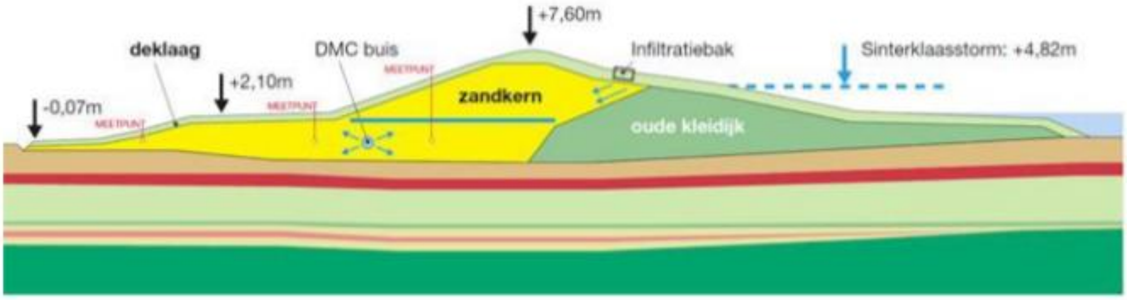


Figure 3. Schematic representation of cross section of original Ommelanderzeedijk (Waterschap Noorderzijlvest, 2018).

Due to increased safety standards for levees in the Netherlands, the Ommelanderzeedijk had to be improved in 2017. It was the first levee of the DFPP in the Netherlands that would be improved according to the new safety standards (Tissink, 2019). In order to meet the new safety standards, the following aspects have been improved. Firstly, the levee has been widened with 25 metres and heightened with up to 2 metres (Nieuwenhuizen, pers. communication). Secondly, the water side has been strengthened by the use of asphalt and hillblocks. Lastly, extra clay depots have been constructed next to the levee. They can be used as a back-up in case of a levee breach. To complete the improvements of the Ommelanderzeedijk, one million cubic metres of sand and 600.000 cubic metres of clay were needed (Tissink, 2019).

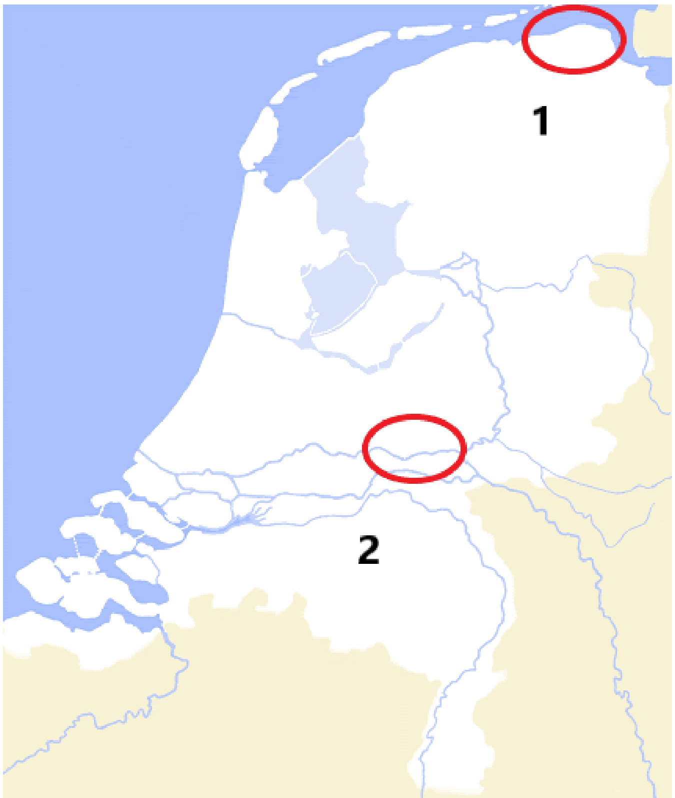


Figure 4. 1) Location of Ommelanderzeedijk. 2) Location of Grebbedijk.

2.3 Grebbedijk

The Grebbedijk is a levee located on the northern shore of the Rhine and is located in the provinces of Gelderland and Utrecht between Wageningen and Rhenen and has a length of 5,5 kilometres (figure 4). Its function is the protection of the Gelderse Vallei against floods. It is a historical clay levee of about two centuries old. The landward berm has been reinforced with a layer of sand. The levee structure is predominantly homogeneous over its length, but the ground below the levee is rather heterogeneous. This has to do with the historical river flow of the Rhine.

Most clay in the levee is gathered locally, because that was the only accessible clay two centuries ago (Bruin & Rookus, pers. communication). This is the case for most levees in the Netherlands. Currently, it is possible to obtain more suitable clay from far away. However, local clays are still preferred for current levee reinforcements due to sustainable demands. Within the rules for sustainability, contractors will keep the production costs as low as possible. In practice, more focus is on the clay quantity instead of the quality (Bruin & Rookus, pers. communication). All clays are divided among three quality categories. Differences between in clay mineralogy are not taken into account for these categories, even though this could be a relevant property (Bruin & Rookus, pers. communication).

Because of the clay content in the Grebbedijk, cracks can be observed in the levee during dry spells. In subsequent wetter periods, these cracks automatically disappear. However, the dry summers of 2018 and 2019 caused cracks of 1,5 metres deep in the Grebbedijk, which remained during winter. More dry summers could lead to deeper cracks that take longer to close. This would result in a higher risk of levee failure and floods. At the moment, adapting to clay cracks is the most important challenge for the water authority of Gelderse Vallei en Veluwe. Currently, the water authority has not found a solution for this problem yet. However, the largest cracks are strictly monitored.

3. Soil aging processes

3.1 Soil properties

All levees have been built on soil and consist of soil. A soil is the upper layer of the earth crust that is rooted by plants in which soil forming processes take place under the influence of climate(Van den Berg & Keizer, 2014). Solid rocks and wet unripe ground – wet sediment, which needs to ripe before it is soil – are not part of it. Every type of soil has its own properties. Soil properties and soil behaviour determine the success and safety of levees. Therefore, levee soils and their interactions with the environment have to be acknowledged. In order to deal with soils – associated with any civil engineering problems and projects – it is necessary to have understanding of mechanics, testing, material science and soil geology. It is necessary that specializations – such as chemistry and biological science – should be included to fully understand soil properties. Stability of the soils in levees are influenced by multiple geochemical, microbiological and time-dependent phenomena (Mitchell & Soga, 2005). The effect of climate change in the Netherlands could have a major influence on the soil properties and thus the levee stability (Vardon, 2015). However, since soil properties are influenced by changes in temperature, pressure, water availability, chemical and biological environment, and other factors, the mechanics of earth materials are complicated. It is of high importance to understand exactly how soil processes change in order to maintain safe and stable levees in the Netherlands (Mitchell & Soga, 2005).

For this report, the focus will be mostly on some of the less typically obtained soil properties (table 1). So far, hardly any research has been conducted on these aspects, many effects are unknown regarding climate change and its effect on relevant soil processes in levees. Levee engineers mostly focus on the typically obtained soil properties on which a significant amount of researches has been conducted. Therefore, it is important to focus on the more unknown soil processes. This report focuses on the ***general soil erodibility***, ***shrink-swell processes***, ***soil salinization***, ***vegetation in soils***, ***and soil organic matter processes***. These processes all are influenced by climate change in its own way. Therefore, initial findings regarding the soil processes have been used to determine the influence of climate change on the aforementioned soil processes and thus the stability of the levee.

Initially, ***bio-activity and fauna in soils*** would have been included in this report as well. However, the influence of climate change on bio-activity and fauna in soils is rather unknown as research has barely been conducted. Notwithstanding, bio-activity and fauna in soils do have major implications for levee stability and have been discussed in other sections and the recommendations.

Table 1. Soil and water properties that influence the erosion resistance of soils (Briaud et al., 2019).

More Typically Obtained Properties	Less Typically Obtained Properties
• Plasticity index • Liquidity index • Unit weight • Water content • Undrained shear strength • Percentage passing sieve #200 • Percentage of clay particles • Percentage of silt particles • Mean grain size • Coefficient of uniformity • Percentage of compaction (for man-made soils only) • Soil swell potential • Soil void ratio	• Specific gravity of solids • Soil dispersion ratio • pH (flowing water and pore water) • Salinity of eroding fluid • Organic content • Soil cation exchange cap • Soil clay minerals • Soil sodium adsorption ratio • Soil activity • Soil temperature • Density of cracks

3.2 Soil erodibility

The erodibility of soils is an important aspect regarding the construction of levees. The erodibility of a soil can be described by a relationship between the hydraulic shear stress or fluid velocity and the soil erosion rate. However, the erosion resistance of soils is influenced by many soil properties (table 1). Therefore, the erosion rate per soil type can highly vary. Existing field and laboratory erosion soil test show different outcomes. This makes it difficult to make a perfect and consistent overview of the erodibility of all soils (Briaud et al., 2019).

A recent report by Briaud et al. (2019) aimed to give a general overview of the erodibility of sand, silt and clay. In order to do this, multiple soil erosion tests were conducted on different soil samples with different techniques and equipment. The three most important techniques they used were the erosion function apparatus (EFA), the jet erosion test (JET), and the hole erosion test (HET). EFA was developed to assess the erodibility of cohesive and noncohesive soils including sand, silt and clay. JET was developed as a testing device for in situ soil erodibility measuring. HET was developed as a laboratory erosion test that evolved from an older erosion test: the pinhole erosion test. More information about the tests and the advantages of each test can be found in the report by Briaud et al. (2019).

Briaud et al. (2019) used the following parameters in order to determine the erodibility of sand, silt and clay:

- **Erosion rate**. Depending on the testing method, the erosion rate of soils can be determined in different ways.
- **Slope of erosion function.** It can be determined in two different forms: erosion rate versus hydraulic shear stress (E_t) and erosion rate versus velocity (E_v).
- **Critical Velocity/Shear Stress.** They refer to the induction of the erosion process. The critical velocity (v_c) refers to the maximum water velocity that the soil can endure without getting eroded. For hydraulic shear stress, the value is accepted as the critical shear stress (t_c).
- **Erosion category.** Briaud (2008) developed erosion category charts in order to make it accessible to determine the erodibility of soils. This erosion chart is based on many years of conducting erosion tests. Figure 5 depicts the erosion categories (EC), in which the lines give the boundaries between the categories in critical shear stress and critical velocity.

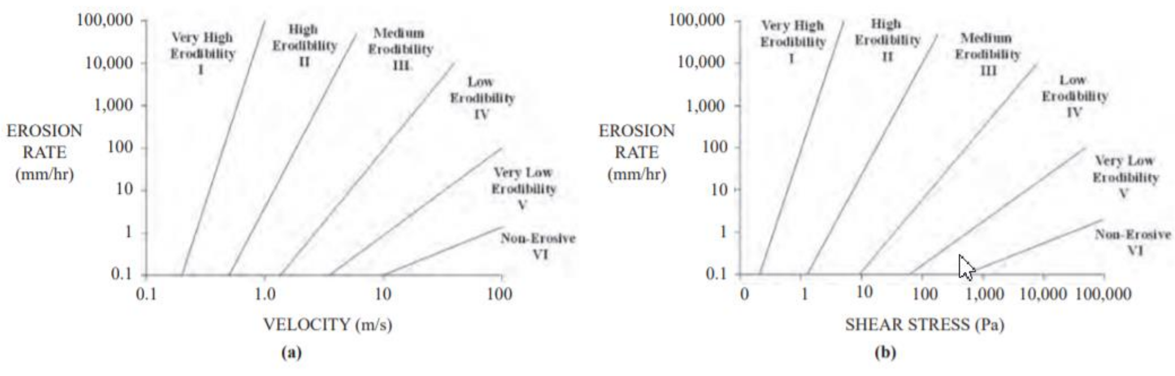


Figure 5. Erosion categories for rocks and soils determined by (a) velocity and (b) shear stress (Briaud, 2008).

The most relevant values from the report by Briaud et al. (2019) for the erodibility parameters are listed in table 2. Full equations and calculations can be found in the report (Briaud et al., 2019).

Table 2. Erodibility values for sand, silt and clays. D_{50} is the mean particle size. t_c is critical shear stress, v_c is the critical velocity, E_t is the erosion rate versus hydraulic shear stress. E_v is erosion rate versus velocity, and EC is the erosion category.

Soil size	Erodibility parameter	EFA	JET	HET
Sand *Average mean particle size of 0.2 mm*	t_c	0.074mm < D_{50} < 0.3 mm **0.46 Pa**	D_{50} < 0.3 mm **7.54 Pa**	
	v_c			D_{50} > 0.074 mm **0.016 m/s**
	E_t	D_{50} > 0.074 mm **64.8 mm/h-Pa**	D_{50} > 0.074 mm **130.2 mm/h-Pa**	
	E_v	D_{50} > 0.074 mm **404.6 mm-s/m-h**		
	EC	0.074mm < D_{50}< 0.3 mm **1.42**	D_{50} < 0.3 mm **1.73**	
Silt *Average mean particle size of 0.037 mm*	t_c	D_{50} < 0.074 mm **0.74 Pa**	D_{50} < 0.3 mm **10.47 Pa**	D_{50} < 0.3 mm **51.9 Pa**
	v_c	D_{50} < 0.074 mm **0.41 m/s**		
	E_t	D_{50} < 0.074 mm **0.78 mm/h-Pa**	D_{50} < 0.074 mm **1088 mm/h-Pa**	D_{50} < 0.074 mm **1.13 mm/h-Pa**
	E_v	D_{50} < 0.074 mm **4.3 mm-s/m-h**		
	EC	D_{50} < 0.074 mm **2.3**	D_{50} < 0.3 mm **2.72**	D_{50} < 0.074 mm **3.1**
Clay *Average mean particle size of 0.001 mm*	t_c	D_{50} < 0.074 mm **53.7 Pa**	D_{50} < 0.3 mm **9.3 Pa**	D_{50} < 0.3 mm **20.5 Pa**
	v_c	D_{50} < 0.074 mm **0.75 m/s**		
	E_t	D_{50} < 0.074 mm **7×10^{-11} mm/h-Pa**	D_{50} < 0.074 mm **0.1 mm/h-Pa**	D_{50} < 0.074 mm **0.39 mm/h-Pa**
	E_v	D_{50} < 0.074 mm **1.6×10^{-6} mm-s/m-h**		
	EC	D_{50} < 0.074 mm **3.3**	D_{50} < 0.3 mm **3.0**	D_{50} < 0.074 mm **3.34**

Briaud et al. (2019) mentioned the following results regarding the erodibility of soils: Firstly, an increase in D_{50} causes an increase in the erosion resistance of soils with a D_{50} greater than 0.3 mm. However, for soils with D_{50} smaller than 0.3 mm, an increase in D_{50} causes a decrease in the erosion resistance. Secondly, in all soils, an increase in clay content causes an increase in the erosion resistance of a soil. Thirdly, an increase in the plasticity index causes an increase in the erosion resistance of all soils. Lastly, an increase in water content of a soil causes an increase in the erosion resistance of the finer soils. However, for coarse-grained soils, an increase in water content could cause a decrease in the erosion resistance.

The report of Briaud et al. (2019) indicated the erodibility of sand, silt and clay in a more general and quantitative approach. The following soil processes – which will be elucidated in the following sections – do have an influence on the erodibility of all soil types. Moreover, these soil processes and soil erodibility are affected by climate change. Therefore, the influence of climate change on several soil processes could lead to a change in the general erodibility of sand, silt and clay soils. This could have major implications for the stability of levees.

3.3 Shrinking and swelling of clay soils

Process of shrinking and swelling

Shrinking and swelling of clay soils can be characterized by ground movement or subsidence caused by clay soils that shrink when they get dry and swell when they get wet and therefore increase in volume (British Geological Survey, 2012). This process occurs due to changes in the moisture content of clay-rich soils. Shrinkage can cause soil desiccation and cracks, while swelling can cause soil heaving and uplifting. The shrink-swell process is determined by the type of clay and the moisture content near the surface. For instance, a fine-grained clay soil can absorb substantial amounts of water, becoming heavy and sticky, causing swelling (British Geological Survey, 2012). The process of swelling is determined by intercalation of water molecules entering to the inter-plane space of smectite clay minerals. Chapter 3.4 will elucidate on this process. Contrarily, the same type of clay can also become very dry and very hard, causing shrinking and desiccation of the clay soil (Taboada, 2004).

The shrinking of soils with clay content contains four stages: structural shrinking, normal shrinking, residual shrinking and zero shrinking (figure 6). During the structural shrinking stage, the volume of the moisture decreases, while the volume or the soil remains stable. During the normal shrinking stage, the moisture volume and soil volume decrease in the same ratio. This means that the soil aggregates remain fully saturated. During the residual shrinking stage, the moisture volume decreases faster than the soil volume. In the last stage, the moisture content slightly decreases, while the volume of the soil remains the same (van den Akker et al., 2014). Shrink-swell processes in soils are mainly dependent on the clay content of the soil (Boivin et al., 2006; van den Akker et al., 2014). The higher the clay content and organic matter content of the soil, the more vulnerable the soil is to shrink-swell processes (van den Akker et al., 2014). Soil shrinking and desiccation especially occur in soils with a clay content higher than 17% (van den Akker, pers. communication).

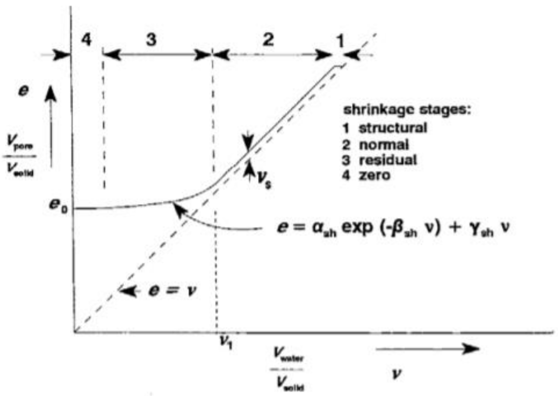


Figure 6. Shrinkage characteristics. V = pore volume; V = volume of solid parts; V = moisture volume; e = pore ratio; v = moisture ratio; α, β, and γ are dimensionless fit parameters (Kim, 1992).

It is important that a soil already has been ripened and is not still sediment before it is used for levee construction. Ripening is the process in which sediment is being transformed into soil. During this process, shrink processes, soil desiccation and soil cracking is very likely to occur. Normally, the process of ripening takes 2 to 7 years in the Netherlands (Vermeulen et al., 2003). The Netherlands still has a significant amount of non-ripened sediments, which would be unsuitable for instance levee construction (Van den Akker et al., 2013).

The process of shrinking and swelling of clay soils can cause damage to levees and embankments and therefore has to be taken into account during the design of the construction. Soil desiccation and soil shrinkage can cause an enhanced permeability of the levee and thus erosion (Vardon, 2015). The main potential failure mode that can be caused by shrink-swell processes is erosion of impermeable layer, piping, internal erosion and slope instability (Vardon 2015). The latter is caused by a reduction of the effective stress and thus the shear strength (Clarke et al., 2006).

Shrink-swell processes and the influence of climate

Shrink-swell processes are also determined by time and meteorological/climatological processes (Figure 7). Droughts will cause shrinking of the soil and desiccation of the soil, while wet periods will cause swelling. Especially extreme precipitation after a drought could cause problems to infrastructure or levees, causing major changes in pore-water due to shrink-swell mechanisms (Vardon, 2015; Medjnoun & Bahar, 2016). Due to the impacts of climate change, the Netherlands is experiencing and will experience higher annual precipitation rates, more droughts, more extreme precipitation and higher annual temperatures (Tank et al., 2014). Some studies have found that enhanced pore-pressure cycles due to climate change could induce progressive collapse of levees (Clarke et al., 2006). Due to this process, the permeability of the soil will be enhanced, causing decreasing stability. Moreover, pore-pressure cycles caused by shrink-swell processes can cause strain softening and irreversible deformation (Hudacsek et al., 2009). While normal pore-pressure cycles and shrink-swell processes normally do not cause major damage, the combination of severe droughts followed by extreme precipitation could be problematic (Vardon, 2015). In an extreme rainfall event moisture can propagate through desiccation cracks more than 10 metres deep, affecting the unsaturated zone. This can affect the slope stability and cause piping (Baram et al., 2012).

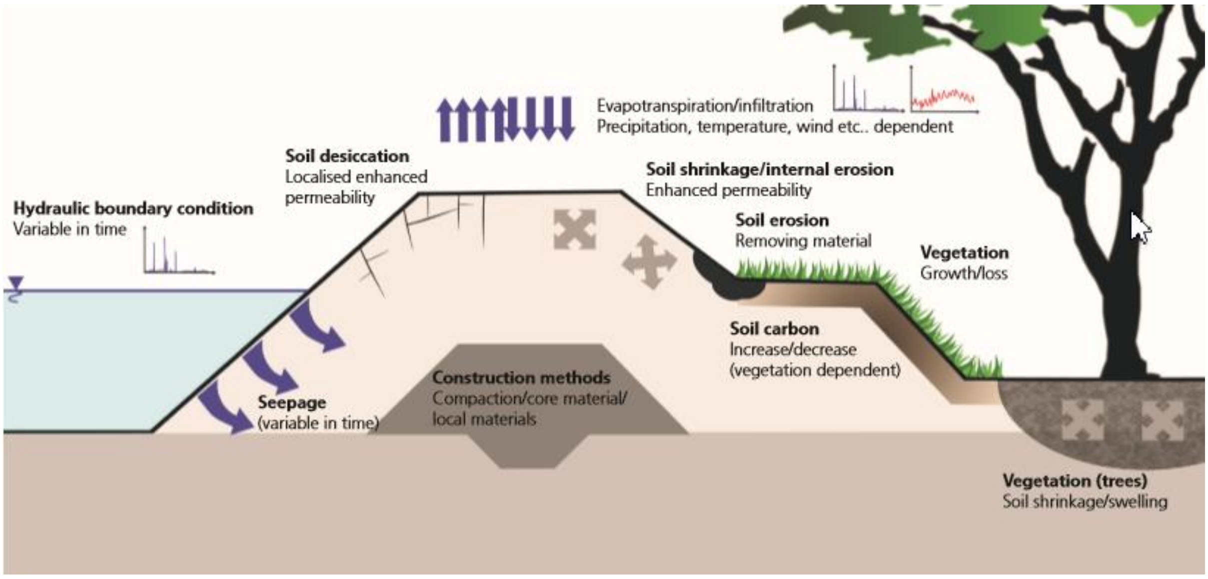


Figure 7. Potential climate interactions with dominantly shrink-swell processes in a levee (Vardon, 2015).

Research on the influence of climate change on shrink-swell processes has been conducted in south-east England (Harrison, 2012). It has been found that not only a change in precipitation has a major influence on shrink-swell processes, but that also increased summer temperatures play a major role. Even in a low-emission scenario, a significant increase in shrink-swell processes will occur in south-east England (Harrison, 2012). Since the Netherlands experiences similar temperatures and precipitation rates and will be affected by climate change in a similar way, it can be expected that that climate change will increase shrink-swell activities in clay levees in the Netherlands.

Similar observations have been found by a study in France, in which droughts and extreme heat increase the occurrence of shrink-swell processes causing soil desiccation and soil subsidence and damage to infrastructure (Corti et al., 2009). The climate of France is a very important proxy for the future climate of the Netherlands. According to the Tank et al. (2014), the future climate in the Netherlands will be comparable to the cities of Nantes and Bordeaux, located in southwest France.

An indicator to determine shrink-swell processes is the annual cycle of wetting and drying due to seasonal changes in precipitation and temperature throughout the year (Clarke & Smethurst, 2010). It has been found that for south-east England and also for the Netherlands that under all future climate scenarios the average and maximum soil moisture deficit will increase, and runoff will decrease. Recent dry and hot summers will become the standard for 2050 (Clarke & Smethurst, 2010). Wetter winters combined with hotter and drier summers will lead to an amplification of soil moisture cycles, which will enhance problems regarding shrink-swell processes in clay soils (Clarke & Smethurst, 2010).

Interlink between shrink-swell processes and other soil processes

Vegetation and the influence of climate change on vegetation itself have an influence on shrink-swell processes (Richards et al., 1983; Clarke & Smethurst, 2010). Although vegetation can contribute to the stability of the slope, it can also enhance shrink-swell processes under influence of meteorological and climatological factors. However, this is highly dependent on the type of vegetation (Tsiampousi et al., 2017). It has been found that mainly trees could highly contribute to soil shrinking and desiccation on levees. Because trees could bring potential damage to a levee, they are not preferred as vegetation (van den Akker et al., 2014). While vegetation does not have a significant influence on shrink-swell processes and slope stability in levees during wet periods, it does have an influence on shrink-swell process in dry periods due to the increasing water demand for vegetation. It is likely that patterns of vegetation growth will change during droughts. This could lead to decreasing moisture content and desiccation of soils at even greater depths because of the plant rooting to greater depths (Hughes et al., 2009). The forecasted future climate scenarios for the Netherlands could enhance the effect of vegetation on shrink-swell processes. However, further research should be conducted on the effects of climate change on vegetation ,rooting depths, water uptake and shrink-swell processes (Clarke & Smethurst, 2010).

A last note is that animals in levees can dig holes and tunnels within the levees. These tunnels can be formed by for instance mice, rats, muskrats and beavers. The process of bio-activity is a major threat for the stability of levees. Existing cracks due to the shrinkage of the clay soils can be expanded by the animals, leading to increased levee damage (Bruin & Rookus, pers. communication). Due to the expected increase of droughts in the Netherlands, animals will enhance and connect existing cracks more easily, damaging the levee even more.

Salization could also have an effect on shrink-swell processes. This process will be elaborated on in the next chapter.

3.4 Salinization

Salinization is the accumulation of soluble salts of sodium, magnesium, and calcium in soil. This influences shear strength, compressibility, shrinking and swelling, and erodibility of clayey soils. The shear strength is a parameter used to quantify the strength of a levee. This property is usually measured by means of the concept of effective stress. However, this approach does not account for chemical interactions between pore fluid and solid particles. Still, on microscale, interactions between solid particles, soluble particles, and water molecules do occur. The water content of a soil determines in which of the four states (solid, semi-solid, plastic, liquid) the soil occurs. The water contents at which a soil shifts from one state to another are called the Attenberg limits. As the Attenberg limits of a clay are determined by interactions between clay minerals and the liquid(water) between them, chemical modification of the clay material could have an influence on long-term mechanical and hydraulic behaviour of natural and engineered clays (Schmitz, 2004). Therefore, it is important to take the effect of salinization into account when assessing the strength of a clay.

Interaction of salt and clay mineral sheets

The extent to which salinization influences the compressibility and shear strength of a soil is determined by the type of aluminosilicates present in the soil. Aluminosilicates are minerals which are composed of aluminium (Al), silicon (Si), oxygen, and counter-cations (i.e. positively charged ions). There are two types of molecules which form the basis of the structure of aluminosilicates. The first is the most basic one, is the tetrahedral silica (Si) molecule, where one silica atom is surrounded by four oxygen atoms. The second is a slightly more complex, octahedral aluminium (Al) molecule, where one aluminium/iron/magnesium atom surrounded by six oxygen atoms. In clays, these molecules link to each other to form sheets. The way these sheets are oriented with respect to each other is the basis of clay classification. In this classification scheme, clays are either 1:1 or 2:1, where variations in center molecules (Al,Fe,Mg) and presence of certain cations form subgroups. A 1:1 clay is an alternation of a sheet of Si tetrahedra followed by a sheet of Al octahedra and so on, whereas a 1:2 clay is formed by repetition of two tetrahedral sheets with an octahedral sheet in between (Figure 8). The three most occurring mineral groups are Kaolinites (1:1), smectites/montmorillonites (2:1), and Illites(2:1) (Barton, 2002). These minerals are also dominant in Dutch clays (Griffioen, 2016).

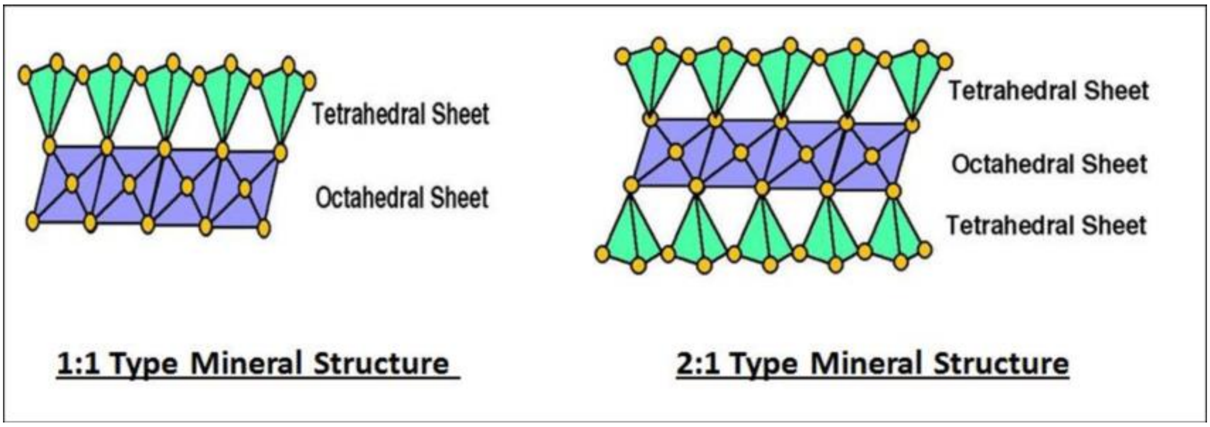


Figure 8: Clay mineral structures (Marchuk & Serhiy, 2016).

These groups of two or three sheets are stacked, which results in the unique clayey substance. The way these stacks are bonded explains how different types of clay minerals respond differently to swelling or salinization. The kaolinite (1:1) sheets are held together by hydrogen bonds, which are strong enough to prevent hydration or infiltration of ions. The sheets of 2:1 clay, such as smectites, are bonded by weaker van der Waals forces, which results in high plasticity. This structure also causes these types of clays to be highly influenced by salinization and hydration (Di Maio 1996; van Paassen, 2004). Even when present in small percentages, smectite increases the vulnerability of a soil to salt water due to its large capacity to cause swelling and dispersion (Churchman, 1993). Moreover, salinization causes the liquid limit of smectite/montmorillonite clays to drop considerably. Several studies found that the liquid limit of bentonite (a smectite clay) drops from 400-376% to 120-150% when a NaCl solution with an equivalent of sea water (0.6M) was injected into the pore fluid, which is shown figure 9 below (Di Maio, 1996; van Paassen, 2004).

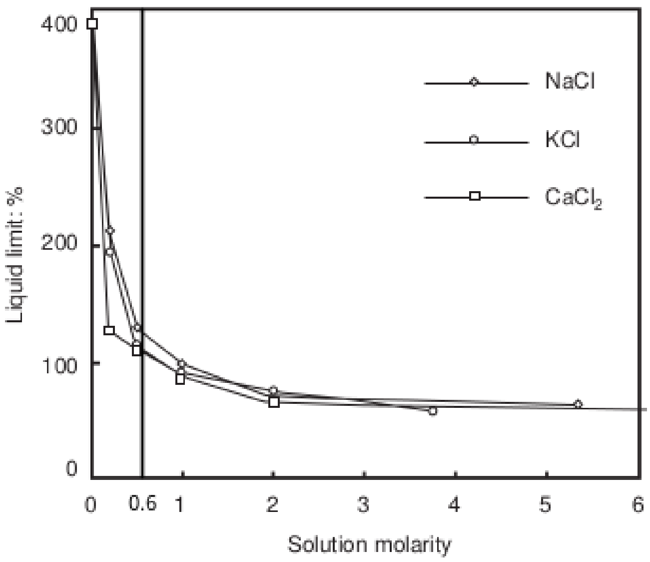


Figure 9: Response of the liquid limit to exposure to salt solutions. The 0.6 line indicates the molarity of sea water (adapted from: Di Maio, 1996).

Such response of the liquid limit is found to be a proxy upon which mechanical parameters can be predicted (Schmitz, 2004). Sharma & Bora found that the undrained shear strength of a clay at the plastic limit is 100 times as strong as at the liquid limit (Sharma, 2003). Decreasing the liquid limit by a factor of around three thus might have negative consequences for the shear strength of a clay.

On the other hand, introducing NaCl in the pore fluid can have positive consequences on the strength of a smectite clay. When no salt is present, the positive side of water molecules adsorb to the negatively charged clay particles. The dipolar nature of the water molecule allows for a second layer of water molecules adsorbed with the same orientation, forming a thick “double diffuse layer”. When NaCl is introduced, the relatively small molecules replace the double layer of water molecules, thus reducing the space between the clay particles, which is illustrated in figure 10 below. This process results in a higher compressibility, shrinking, and increase in shear strength (Di Maio 1996; Tiwari 2005; Pineda 2013). This process is completely reversible for NaCl, which is not the case for other salts, such as CaCl and KCl. When fresh water is reintroduced, the properties of the clay return to the initial state as if no salt was added (Di Maio, 1996).

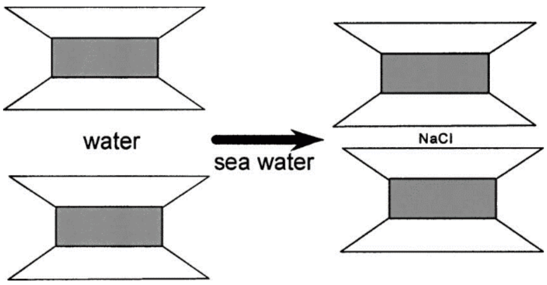


Figure 10: Compaction by introducing NaCl to 2:1 clay minerals (Di Maio, 1996).

Shrinking and swelling
Salinization has a large effect on the swell capacity of clay soil (Durotoye et al., 2016). Salinization of soils is a process that occurs on a large scale in the Netherlands due to its location nearby the sea. A study by Durotoye et al. (2016) found that an increase in the amount of sodium chloride in California soils causes a reduction in the swell capacity of clay soils. Therefore, desiccation and the forming of big cracks is less likely to be restored if the swell capacity is reduced. The influence of sodium chloride - which is the main ion in salinization processes in the Netherlands - could have a negative impact on clay levees in coastal areas in the Netherlands by stimulating shrink-swell processes (Durotoye et al., 2016; Afrin, 2017). When sufficient Na+ ions have replaced water molecules or other exchangeable cations, we speak of soil sodicity or sodic soils (Sen et al., 2019). The swelling effect is the largest when sodic clays get in contact with water containing way less salt (Kruse, 2013; Kruse, 1987). The higher difference in salt concentration between water outside and inside pores of sodic clays, the more water can be absorbed by the clay (Kruse, 2013).

Dispersion and erodibility
Sodic soils are also sensitive to dispersion. Dispersion of a soil is a process in which clay particles are repelled from each other, which causes the soil to break down into small particles.

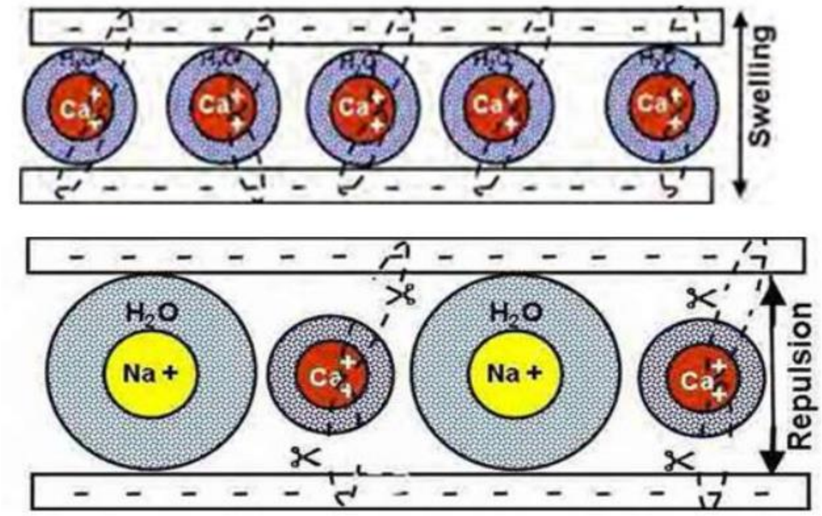


Figure 11: In the upper part, a swelling clay is visible. In this case, the calcium ions keep the clay plates together. In the lower part. Some calcium is replaced by sodium, which absorbs water. As a result, the clay plates will be torn apart. This is called clay dispersion (Sen et al., 2019).

In figure 11, the effect of sodium on clay structures is explained. If present, sodium ions replaced the initial cations. When water is available, the cations adsorb the water and exert force on the clay particles. Sodium takes up more water than other cations. As a result, the clay will swell and lose its structural stability (Sen et al., 2019). The binding between clay plates can break down and the clay deflocculates. That makes dispersive clays very erodible (Sen et al., 2019).

Whether a sodic clay is dispersive or not depends partly on its mineralogy. Each reacts to the circumstances in a different way. For example, illites are dispersive with high electric conductivities because its shape prevents cohesion in that case (Churchman et al., 1993). Kaolinites are dispersive with high pH-values (Churchman et al., 1993). As seen in figure 12, this has to do with the crystal edges turning negative. Smectite shows only limited swelling, because of its fine and flexible structure (Churchman et al., 1993). However, it could still be dispersive.

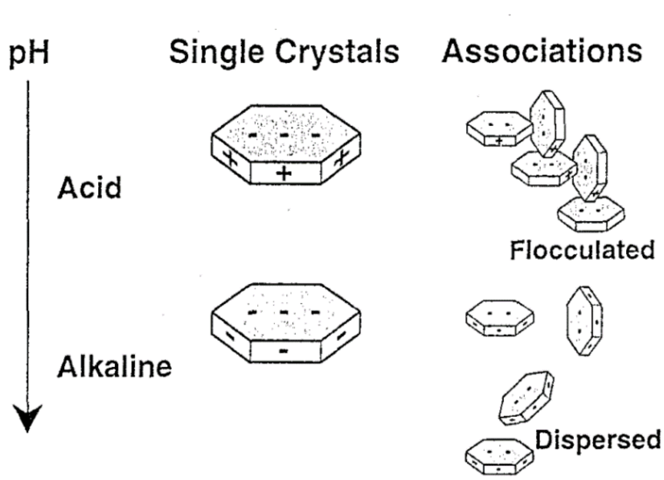


Figure 12: Dispersion of kaolinites occurs at high pH values. The edge of the crystals will get negative with high pH and crystals will repel each other (Churchman et al., 1993).

Interaction of salinization and organic material

Other factors determining the dispersivity of sodic clay soils is the organic matter content. However, scientific papers seem contradictory. Organic matter limits swelling but stimulates dispersion. Swelling is probably suppressed by organic matter because it lowers the reactive surface area (Turchenek and Oades 1978; Schwertmann et al. 1986; Churchman and Oades 1993). The effect on dispersion is variable. With low ESP (Exchanged Sodium Percentage), organic matter increases dispersion (Loveland et al., 1987). With high SAR (Sodium Adsorption Ratio), organic matter decreases dispersion (Gupta et al., 1984). Churchman et al. (1993) mention that organic matter behaves also different with different aridities, minerals and types of organic matter.

3.5 Vegetation

An important part of many soils is its biological component. Especially plants and fungi have an vital role to play in the erosion resistance of a soil (Van der Meer et al, 2012). This protection by vegetation is even more important for soil in levees because by their nature they lie higher in the landscape and are thus more susceptible to erosion then the surrounding soils. This erosion protection is especially essential in case of wave action and overtopping as this can lead to large volumes of water spilling over the levee in a short period of time. Both have the potential of causing rapid erosion (Schüttrumpf & Oumeraci, 2005). Therefore, it is important to know what influences the integrity of the erosion protection provided by vegetation.

The roots and mycorrhiza of plants and fungi prevent erosion by binding the mineral part of the soil. Another way in which roots help to stabilise the soil is by promoting cementation between particles by excreting certain compounds (Van der Meer et al, 2012). Therefore, we can generally say that the more complete the vegetation cover is, the better the soil is braced against erosion (Sprangers, 1996). The extend and depth of this binding is dependent on several factors of which the most important ones will be discussed in this chapter.

Soil structure

One of the most important factors is the structure of the soil. Plant roots can only grow if there is enough space for them to grow. A lot of this space is present in the form of micropores. These are the spaces between soil particles, and they tend to increase with particle size. For example, a heavy clay soil does not provide as much pore space as a sandy soil. Roots can therefore more readily spread through a sandy soil than through a clay soil (Van der Meer et al, 2012).

Moreover, roots can also grow in macropores roots. These are areas of bigger spacing within the soil. This includes the burrows of many soil creatures such as worms, but also the cracks that form as clay shrinks. These pores help plant roots grow deeper than they would do normally, but they also increase the soil layers permeability (Van der meer et al, 2012).

Some soil structure formations disrupt the pore spacing by hindering root or plant growth. Two examples of this are soil crusting and soil smearing/compaction. Physical soil crusting occurs mainly on bare loess and light clay soils. A thin crust forms as the impact of raindrops moves small clay and silt particles in the soil pores. This crust prevents many plant species from establishing themselves, which results in the soil remaining bare for longer periods (Lemos & Lutz, 1957).

Soil smearing/compaction happens with heavier clay soils when they are put under stress while it is saturated. The stress can be caused by heavy machinery or large animals, like cows or horses. The pores in the soil are then pressed and/or smeared shut, creating a layer of clay that is near water/airtight. This prevents water from infiltrating in the soil, air from reaching underlying soil layers and the growth of roots. Thus, all prevent plant growth (Halley, Dumitru, & Dexter, 1995).

Water availability
Another very influential factor regarding the growth of vegetation on levees is the soils ability to provide water. This in turn is again linked to soil type. The smaller the grains (and thus the smaller the pores), the stronger the capillary forces are. As a result, heavy clays have the highest field capacity, but also the highest wilting point (the minimum amount of water in the soil that the plant requires not to wilt). Conversely, sand has a very low field capacity, but also a very low wilting point (Casse & Nielsen, 1986). Combined with the fact that sand has a very high permeability, it causes the water providing capacity of both heavy clay and sand to become inadequate during a period of drought. A hard-baked clay layer is also harmful for the roots growing inside it. This effect is exacerbated on a levee with a mask of heavy clay on top of a body of sand, in which water can easily flow away. In that case, water cannot be drawn up by the negative pressure in the clay layer on top. Plants that naturally grow on clay and depend on water from lower layers to be pulled up can die as a result. In contrast, the soils that are most resilient to drought are the lighter soils like light clay, heavy loam, and light to moderately light sablon. The top layers of these soils dry out quickly, but they protect the layers underneath from drying. Plant roots stay intact and capillary action in the small pores gives the best chance of some of the water making it to the roots. Vegetation on these soils also tends to recover faster after drought than vegetation on heavy clay or sand. In too sandy soils, water would flow away before plants can take it up. In too clayey soil, the low infiltration capacity results in runoff or evaporation instead of water uptake by plants (handreikinggrasbekleding, 2019).

The orientation of a levee is another important factor that influences water availability. The parts of the levee that is orientated towards the sun will dry out more quickly than the parts that are not. This makes the plants on the sunlit side more vulnerable to water shortages as seen in figure 13.

Figure 13. Shadow side (left) sunlit side (right) of a levee in Yerseke (van Grinsven, 2020).

Nutrient availability
The last factor that influences vegetation growth and that will be addressed in this report is nutrient availability. The most important nutrients for plants are nitrogen (N), phosphorus (P), and potassium (K), which are the macronutrients.

In case of a lack of nutrients, fewer plants and more herbaceous plants will grow on the embankment. This will result in an incomplete ground cover, spotted with pioneer species. This incomplete cover makes the ground vulnerable to erosion.

With sufficient amounts of phosphorus, potassium and nitrogen, high biomass production can take place above and below ground. However, there are some serious disadvantages. For example, biomass is mainly produced by fast growing plant species. With enough N these species can outcompete other species leading to low biodiversity. The levee embankment is then dominated by a small number of fast-growing species (Van der Zee, 1992). This leads to several problems.

Firstly the root system of the levee embankment could weaken. Research has shown that although the fast-growing N loving plants produce a more massive root system, this root system is relatively shallow. The dominance of this vegetation type means that the soil protection by vegetation is smaller than in a more biodiverse scenario (Van der Zee, 1992; Sprangers, 1996).

Secondly, these fast-growing plants literally overshadow their surroundings. This results in bare patches between patches of grass. This incomplete vegetation cover makes the soil more vulnerable to erosion (handreikinggrasbekleding, 2020).

Thirdly, the decrease of plant species or low biodiversity, only occurs under extreme circumstances such as drought. If circumstances change in a way that is unfavourable to a certain plant species it can locally die off. With healthy diverse vegetation cover this is not a big problem as there are many other species still remaining. But in a uniform vegetation cover the disappearance of a single species can leave the vegetation cover seriously compromised (handreikinggrasbekleding, 2020).

3.6 Organic matter processes

Organic material is formed by plants via photosynthesis. Therefore, vegetated soils contain organic material. When this is present, some important processes take place in the soil that are mentioned below. These processes can occur in levees or in soils near the levees that could be used for levee strengthening.

Oxidation

When organic matter is exposed to oxygen, oxidation reactions occur (TAW, 1996; Van den Berg & Keizer, 2014). The reaction products will escape from the soil. This organic material decay is dependent on several circumstances. Due to climate change, organic matter will be decomposed faster. Rule of thumb is that organic decomposition rates double when temperatures increase with 10 degrees Celsius. This rule is applied to temperatures between 0 and 40 degrees Celsius and unchanging moist conditions (Van den Berg & Keizer, 2014). Besides, the lower the rate of respiration at 20 degrees Celsius, the higher the sensitivity for more soil respiration (Craine et al, 2010). Also, the more biogeochemical recalcitrant the organic matter is, the higher the sensitivity for soil respiration (Craine et al, 2010).

The type of organic material plays a large role for oxidation as well. The more nitrogen and the less lignin are present in the organic material, the faster it will be decomposed (Van den Berg & Keizer, 2014). Another factor is the presence of organisms in the soil, such as worms, that can decompose organic material. Bacteria and fungi do this in a direct way, but also animals have an indirect role by breaking and mixing material. The presence of this animals depends on pH and soil moisture conditions (Van den Berg & Keizer, 2014)

Clay and organic material interaction

Clay and organic material interact with each other. Clay tends to capture decomposition products of plants and animals (Mortland, 1971). Stable clay-aggregates can originate when decomposition products bind with multiple clay minerals. That is why clay soils often contain large amounts of organic material. Clay-organic complexes modifies swelling/shrinking effects. For example, vermiculite clay swelling can be activated due to presence of organic matter (Mortland, 1971). However, organic material may also prevent swelling of other clays. Besides, the presence of salt influences the effect as well. This is further explained in 3.3.

Water repellency

After periods with dry and warm weather, coarse-grained soils rich in organic material may develop water repellency (Tang et al, 2018). This reduces water infiltration and will result in more surface-runoff. Organic material in the form of colloids is able to bind to soil particles. This effect is the largest on sandy soils. When these colloids are located in the pores in between multiple soil particles, they are able clog these pore spaces. In that way, the formation of biofilms takes place. As a result, the water permeability will decrease and the resistance to erosion will increase.

Influence on levees

Summarizing, most important influence of above mentioned processes on levees are:

- Shrink of levee material due to oxidation of organic material.
- Modified swelling/shrinking behaviour of clay soils due to the interaction of organic material, clay and salt.
- Water repellency and erosion resistance due to binding with coarse-grained material.

Levees are mostly covered with a layer of grass. This mostly leads to a dynamic equilibrium with an organic matter content of 3-5% (TAW, 1996). For levees in the Netherlands, the maximum tolerated percentage of organic matter is 5%. The goal is to limit levee shrinking by that way, as the decrease of volume due to organic matter oxidation is considered most influential for the stability of levees (TAW, 1996).

4. Projections of climate in the Netherlands

4.1 Climate modelling

Since the 1960s, models are being developed and improved to predict future weather and climate. As these phenomena are complex, several agencies provide with models, describing different processes, or processes simplified in a varying manner. There are two main reasons for using multiple models to describe different processes. Often, models tend to get less accurate when the complexity increases, a second restriction is the available computing power. More and more processes have been implemented over the years allowed by the continuous technological development of computers. To make climate predictions more wholesome and nuanced, models are combined to form ensemble models. Ensemble models are used by agencies such as the Intergovernmental Panel on Climate Change (IPCC) to model the climate as accurately as currently possible.

To present insight in the Dutch climate in the year 2050, KNMI14 scenarios for climate change were studied and climatic changes relevant to soil ageing processes are summarized below. IPCC's representative concentration pathway (RCP4.5-RCP8.5) scenarios are used as basis for the KNMI14 scenarios, using the KNMI climate model CMIP (Tank et al., 2014). The number behind 'RCP' represents an increase of radiative forcing(W/M) relative to pre-industrial times, which is implemented in the model. This increased radiative forcing alters the earth's radiation balance, and thereby increases the average surface temperature. The 'average' scenario (G) is based on RCP 4.5 scenario, the 'warm' scenario (W) is based on the RCP 8.5 scenario. The reason why two temperature scenarios are presented, is because the increase in radiative forcing is dependent on our future emissions, which is a very uncertain variable. Although RCP8.5 (or in our case "W") is often presented as a "business as usual" scenario, a more controversial view argues that RCP4.5 (or "G" in our case) is a likely future, while the RCP8.5 scenario can be interpreted as worst case (Granger Morgan & Keith, 2008; Ho et al, 2019).

Apart from two possible changes in radiative forcing, KNMI added two sub scenarios, where two different air circulation patterns are modelled, which are denoted with a subscript L(ow) or H(igh). In the H scenarios, westerly winds during winter are more common, resulting in soft and wet winters. In the summer, high pressure areas dominate summers bringing about easterly winds, resulting in drier and hotter summers. In the L scenarios, westerly winds during winter are less common, resulting relatively cold and dry winters. Moreover, in the L scenarios, high pressure areas are less prominent which results in milder, wetter summers (Tank et al., 2014). These sub scenarios are added because the large-scale meteorology is very complex and it not sure how this will develop in the future.

The next section describes relevant changes in the Dutch climate according to data by KNMI (Tank et al., 2014). Yearly and seasonal quantitative data can be found in the table below 4.2.

4.2 Climate predictions

The modelled change in radiative forcing forms the basis for the predicted future climate of the Netherlands. This perturbation in radiative forcing brings about changes in meteorological phenomena. The three most relevant changes for soil ageing processes are temperature increase, changes in precipitation patterns and sea level rise. How these changes vary between season and climate scenario is described below.

Temperature
In all four scenarios, the yearly average temperature in the Netherlands rises. The increase is the highest in winter, followed by autumn, then summer, and the average temperature in spring rises the least. An increase in temperature enhances the amount of evaporation. The relationship between temperature and potential evaporation on grasslands is described by Makkinks formula (Data from Wageningen UR show an increase in potential evaporation since 1928). This formula is used to describe the increase in evaporation in the future and predicts a 2% increase in evaporation for every degree (°C) of warming. As this formula describes the amount of evaporation when sufficient water is available, the actual evaporation rate might be lower in case of limited water availability.

Precipitation
Besides increased evaporation, a higher air-temperature increases the amount of water that can be held by air (Wallace & Hobbs, 2006). These two processes together explain why the average precipitation and the amount of heavy rainfall events increase in every scenario. Extreme precipitation will be more frequent in winter as well as in summer. While the summer suffers intermediate warming, droughts during this season are predicted to increase dramatically. Although the average summer precipitation increases when low change of air pattern circulation is assumed (L scenario), the amount of wet days does not increase as much. This means that heavier rain will fall on wet days, which is confirmed by the increasing amount of days with >20 mm rain, and increasing maximum hourly precipitation rate in all four scenarios.

As the potential evaporation rates rise linearly with rising temperatures, a drier summer climate is very likely. This phenomenon was already visible in the previous two Dutch summers, and currently (May 2020) a record high in precipitation shortage in the growing season is recorded. The prospects for 2050 indicate that this effect will be more severe in the future. Although the average yearly precipitation increases, precipitation shortage in the growing season (April-September) increases in every scenario. This apparent contradiction can be explained by the large increase in rainfall during winter. It must be noted that the calculated precipitation shortages and droughts are probably overestimates, since the models also calculate our current climate as drier than in reality. Still, droughts can be expected to occur more and more frequently.

Sea level rise
Besides, observations reveal an average annual sea level rise of 1.8 mm/y at the Dutch coast since 1900. Unlike the global average sea level rise, rise in the North-Sea shows no clear acceleration apart from natural variations. This is because the natural sea level variations – induced by wind in the North-Sea – are much higher than the global rising sea level. The projected sea level rise in 2050 is up to +40 cm in the W scenario (no difference between L and H here). This is more than in previous calculations, where expansion of the oceans was not included and the rate of melting of land ice on Greenland and Antarctica was estimated to be smaller. Furthermore, sea-level rise is affected only by an increase in temperature, not by changes in air pattern circulation.

The predicted climate change scenarios show a large variation. This is because it is very uncertain what the future climate will exactly look like. However, KNMI’s scenarios indicate that we can expect meteorological changes. How these changes might influence soil processes is described in chapter 5.

Table 3. A quantitative overview of KNMI's future climate predictions (Tank et al., 2014)

Scenario					G_L	G_H	W_L	W_H
Average temperature increase					+1°C	+1°C	+2°C	+2°C
Changes in air Pattern					Low	High	Low	High
Season	Climate Indicator		Historical climate (1951- 1980)	Present climate (1981-2010)	Projected climate change for the year 2050 (2036-2065)			
Yearly	Local Sea Level	Absolute	-4 cm NAP	+3 cm NAP	+15-30 cm	+15-30 cm	+20-40 cm	+20-40 cm
		Rate of change	1.2 mm/y	2,0 mm/y	+1-5,5 mm/y	+1-5,5 mm/y	+3,5-7,5 mm/y	+3,5-7,5 mm/y
	Temperature		9,2 °C	10,1 °C	+1,0 °C	+1,4 °C	+2,0 °C	+2,3 °C
	Precipitation		774 mm	851 mm	+4%	+2,5%	+5,5%	+5%
	Potential Evaporation		534 mm	559 mm	+3%	+5%	+4%	+7%
Winter	Temperature		2,4 °C	3,4°C	+1,1 °C	+1,6 °C	+2,1 °C	+2,7 °C
	Precipitation		188 mm	211 mm	+3%	+8%	+8%	+17%
	Wet days (>0,1 mm)		56	55	-0,3%	+1,4%	-0,4%	+2,4%
	Days with > 10 mm		4,1 days	5,3 days	+9,5%	+19%	+20%	+35%
Spring	Temperature		8,3 °C	9,5 °C	+0,9 °C	+1,1 °C	+1,8 °C	+2,1 °C
	Precipitation		148 mm	173 mm	+4,5%	+2,3%	+11%	+9%
Summer	Temperature		16,1 °C	17,0 °C	+1,0 °C	+1,4 °C	+1,7 °C	+2,3 °C
	Days with T >25 °C		13 days	21 days	+22%	+35%	+40%	+70%
	Precipitation		224 mm	224 mm	+1,2%	-8%	+1,4%	-13%
	Max hourly precipitation		14,9 mm/h	15,1 mm/h	+5,5 to +11%	+7 to +14%	+12 to +23%	+13 to +25%
	Wet days (>0,1 mm)		45 days	43 days	+0,5%	-5,5%	+0,7%	-10%
	Days with > 20 mm		1,6 days	1,7 days	+4,5 to +18%	-4,5 to +10%	+6 to +30%	-8,5 to +14%
	Potential Evaporation		253 mm	266 mm	+4%	+7%	+4%	+11%
	Precipitation shortage grow season (apr-oct)		140 mm	144 mm	+4,5%	+20%	+0,7%	+30%
Autumn	Temperature		10,0 °C	10,6 °C	+1,1 °C	+1,3 °C	+2,2 °C	+2,3 °C
	Precipitation		214 mm	245 mm	+7%	+8%	+3%	+7,5%

5. Possible influence of climate change on levee stability

In chapter 3 the following soil processes have been described: ***Shrink-swell processes***, ***soil salinization, vegetation in soils***, ***and soil organic matter processes***. These processes are all influenced by climate change and could affect levee stability in different ways. Chapter 4 describes how the climate in the Netherlands will change towards the year 2050. This chapter describes how climate change in the Netherlands could influence the aforementioned soil processes and thus the stability of the levee. Table 4 shows the main findings regarding the soil processes, climate change and levee stability.

Shrinking and swelling

An expected increase in droughts in the Netherlands is very likely to cause an increase in soil shrinking, soil desiccation and soil cracking. These processes could lead to problems regarding piping, internal erosion, and slope instability for existing levees. For new levees, this could lead to serviceability failures and additional costs (Vardon, 2015). The problems regarding drought-induced shrink-swell processes could be enhanced by the behaviour of vegetation and salinization. The vegetation density could be reduced by droughts, causing a decrease in the stability (Tsiampousi et al., 2017). At the same time, the water demand of vegetation during droughts will increase, causing a larger water deficit. This could lead to an increase in soil cracking (Hughes et al. 2009; Clarke & Smethurst, 2010). Salinization – which will be enhanced due to an increase in seepage due to sea level rise – in the form of sodium chloride could reduce the swell capacity of clay soils (Durotoye et al., 2016). This process would not allow to let the cracks restore. Higher temperatures and extreme heat combined with droughts in summer will enhance problems regarding soil drying, soil desiccation and soil cracking (Corti et al., 2009). Until recently, there was not so much attention for droughts in the Netherlands for clay levees. However, the summers of 2018 and 2019 indicated that droughts could be a major problem for levees in the future (STOWA, 2019; Bruin & Rookus, pers. communication).

An expected increase in annual precipitation and more extreme precipitation would initially not affect the shrink-swell processes in clay soils in the Netherlands. However, the combination of wetter winters and warmer and drier summers will lead to an amplification of soil moisture cycles, which could enhance problems regarding shrink-swell processes in clay soils (Clarke & Smethurst, 2010). Especially the combination of droughts followed by extreme precipitation could cause problems, such as piping, slope instability, and serviceability failure (Baram et al., 2012; Vardon, 2015).

Salinization

Sea levees suffer under increasing pressure due to continuously rising sea levels. Apart from the increased direct hydrostatic stress on the levee, sea level rise could induce salinization of levees, especially in combination with droughts. Precipitation in the Netherlands decreases salt water seepage. Therefore, in periods of drought, more salt water will enter the groundwater and could reach levees further inland (Kroes & Supit, 2011).

Although the exact mineral composition of levee clays has not been studied, smectite is a mineral which is abundant in Dutch clays (Griffioen, 2016). As this mineral causes instability in clay soils, it is likely that Dutch clay levees are vulnerable to salinization. At this moment, soil sodicity is not expected to have a large impact on levees strength in the Netherlands. However, warm and dry weather will be more frequent in the future (chapter 4), which increases the exposure of salinization on clay levees. One of the climate projections from KNMI shows comparable climate conditions with southern France. In the Mediterranean area, sodicity in clay soils is more likely to be found. Sodium is transported with seepage and especially clay soils in coastal regions are therefore vulnerable for sodicity (Kruse, 1987). That could make soils less suitable for levee reinforcement. Levee soils themselves are less vulnerable for sodicity as the groundwater table is deeper there. Also splash water can contribute to sodicity (Kruse, 1987). However, this salt from splash water mostly flushes away with precipitation. Sand and silt are not so much impacted by sodicity.

Vegetation

Vegetation growth is inherently linked to climate, because one of the factors that influences the growth of vegetation is the availability of water. A change in water availability will influence the state of vegetation on levees. Because levees themselves are raised above the surrounding land, it is not expected that a surplus in precipitation has much influence on the state of vegetation on levees. Contrarily, an increase in the precipitation deficit could have negative effects on the integrity of the vegetation on levees as a result of the processes discussed in chapter 3.5. As droughts in the Netherlands become more prevalent, it is expected that die-offs in vegetation also become more common. As discussed before, certain factors may worsen these effects. Among these are the soil types used to build the levee as discussed in chapter 3.5. The diversity of vegetation also impacts the resilience of the vegetation as a whole. Therefore, nitrogen pollution could have a synergetic effect with climate change on the integrity of levee strength as mentioned in chapter 3.5.

Organic material

Most important influences of organic matter on levees are:

- Shrink of levee material due to oxidation of organic material.
- Modified swelling/shrinking behaviour in clay soils due to the interaction of organic material, clay, and salt.
- Water repellency and erosion resistance due to binding with coarse-grained material.

For levees in the Netherlands, the maximum tolerated percentage of organic matter is 5% to limit the first mentioned process. The direct impact of climate change is the increase of organic matter oxidation rate due to droughts and higher temperatures, which will shrink soil in levees irreversibly. As a result of lower organic matter content, coarse grained soils will be less resistant for erosion. However, the effect of less present organic matter on swelling/shrinking in clays is variable. Also, mineralogy and water availability are more important for swelling/shrinking in clay soils than the organic matter content.

Ommelanderzeedijk & Grebbedijk

The top clay layer and the old clay embankment on the water side of the Ommelanderzeedijk could be vulnerable to the expected increase in droughts during the summer, which could cause soil desiccation and soil cracking (Vardon, 2015). As of today, no problems regarding droughts or increased and extreme precipitation have occurred near the Ommelanderzeedijk. This also applies to problems regarding salinization and vegetation (Nieuwenhuizen, pers. communication). However, amplification of the groundwater level variation in the sandy part of the levee have been observed due to the increasing precipitation contrast between winter and summer. It is likely that that the amplification of the soil moisture cycle and the occurrence of severe droughts will increase and could possibly lead to problems (Clarke & Smethurst, 2010). Therefore, it is recommended to focus mostly on problems regarding droughts near the Ommelanderzeedijk in the future.

For the Grebbedijk, droughts during summers are the main problem as well. In contrast with the Ommelanderzeedijk, problems regarding drought already occur at the Grebbedijk (Bruin & Rookus, pers. communication). As the levee consists dominantly out of clay, it is vulnerable to shrinking and swelling. During the summers of 2018 and 2019, this caused cracks that remained during winter. Moreover, dry circumstances attract animals like moles and rats. They connect the cracks to each other by digging corridors, resulting in even more damage. A long-term solution for the cracks has not been found yet. Problems with vegetation and salinization have not occurred yet. However, salt water could potentially reach the groundwater below the Grebbedijk in a drier climate (Bruin & Rookus, pers. communication). This may cause more problems in the future.

Overview of influence of climate change on soil ageing processes and levee stability
Table 4 shows the main findings regarding the soil ageing processes, climate change and levee stability. It was intended to provide a quantitative table for the erodibility of the different soil classes and soil processes, like the erodibility table by Briaud et al. (2019) in chapter 3.2. However, it appeared that the studied soil ageing processes are too difficult to quantify. All the soil ageing processes would need specific field tests to quantify the erodibility of the different soils with different soil processes and climate scenarios. Notwithstanding, a qualitative table is constructed regarding the soil ageing processes, climate change and levee stability. The soil classification triangle below (figure 14) is based on Verruit & Baars (2005). The soil categories from the triangle are used in the table.

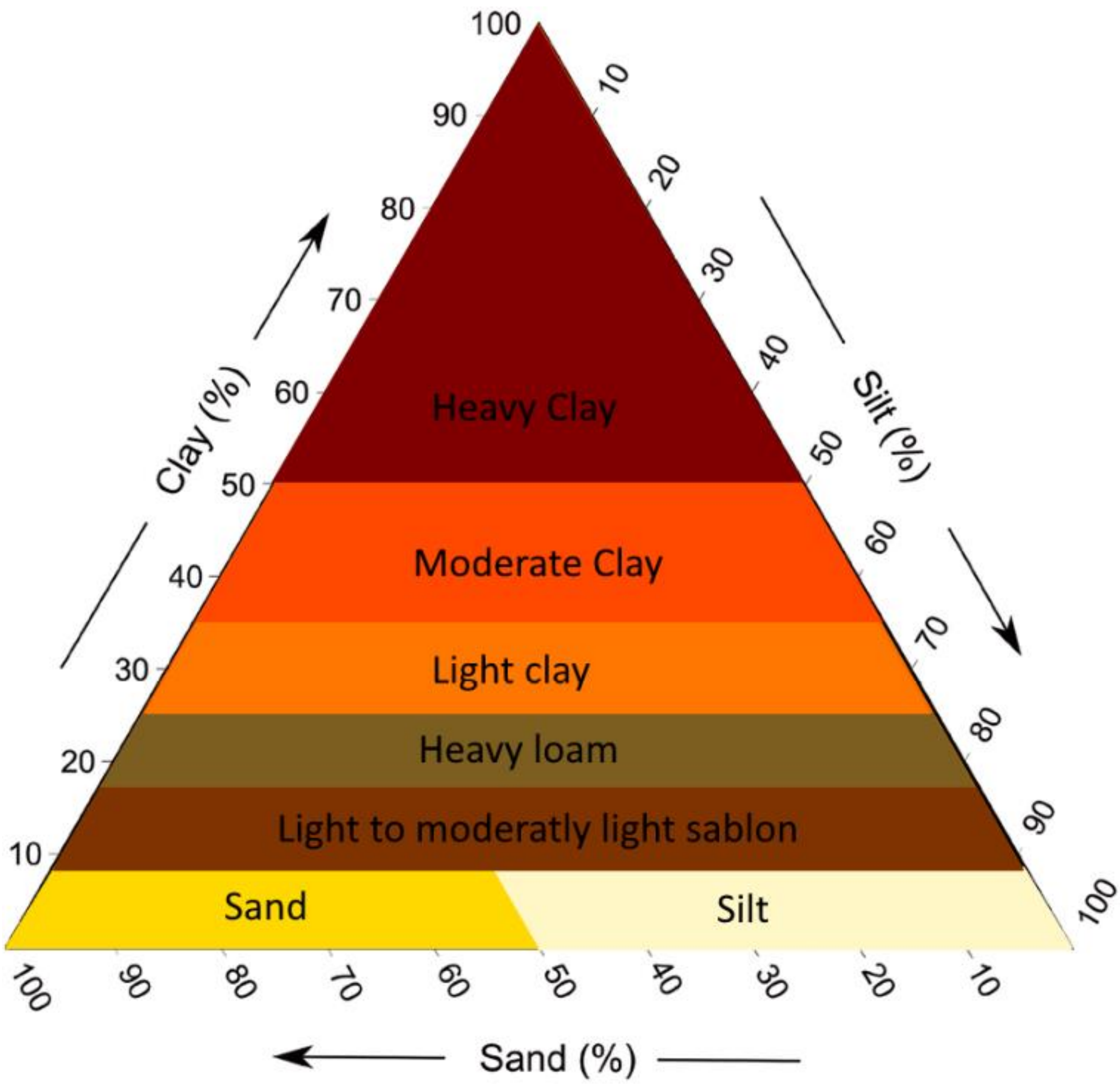


Figure 14. Soil categories (Verruijt & Baars, 2005)

Table 4. Schematic overview of the influence of climate change on soil processes and levee stability.

(Mask) Material	Shrinking/Swelling	Organic matter	Salinization	Vegetation	
				Sand like earth fill material	**Clay like earth fill material**
Sand (zand)	Shrink-swell processes are not relevant for sandy, silty soils, and light to moderate sablon soils.	Could form an impermeable layer that reduces infiltration and increases surface runoff.	Little to no effect.	Vulnerable to drought if not enough deep rooting species are present.	Situation not applicable
Silt (silt)		Not coarse enough for impermeable layer due to organic matter.		Slightly vulnerable to soil crusting on bare soil if not enough organic matter is present. moderately resilient to drought.	
Light to Moderately light sablon (lichte tot matig zware zavel)		The higher the clay fraction, the more influence of organic matter on shrink/swell processes by organic matter-clay aggregates.	Small percentages of clay could cause volumetric changes and dispersion, dependent on the smectite content.	Vulnerable to soil crusting on bare soil if not enough organic matter is present. But very resilient to drought.	

<table>
<tr>
<td>Heavy loam
(zware zavel)</td>
<td rowspan="4">Shrink-well processes occur at a clay content > 17%. Increasing contents lead to increase in shrink-swell processes

Increase in droughts:
Soil shrinking, soil desiccation and vegetation reduction leading to
External erosion
piping
internal erosion
slope instability.
For new constructions
serviceability failures
additional costs
Increased temperature:
Drying, soil shrinking and soil desiccation leading to
piping
internal erosion
slope instability.
Increased annual precipitation and extreme precipitation:
Increased soil moisture cycles, enhancing shrink-swell induced problems as
piping
slope instability.
Increase phreatic line</td>
<td></td>
<td>Vulnerable to swelling, dispersion and changes in soil strength when clay fraction is dominated by smectite.</td>
<td colspan="2"></td>
</tr>
<tr>
<td>Light Clay
(lichte klei)</td>
<td rowspan="3">Organic matter-clay aggregates could be formed, changing swelling behaviour.</td>
<td>Vulnerable to swelling, dispersion, and changes in soil strength when exposed to salt depends on the smectite content of the clay.</td>
<td colspan="2">Resilient to drought and fast to recover.</td>
</tr>
<tr>
<td>Moderate Clay
(matig zware klei)</td>
<td>Very vulnerable to swelling, changes in soil strength, and dispersion when exposed to salt.</td>
<td>Susceptible to drought and slow to recover.</td>
<td>Not very susceptible to drought but slow to recover.</td>
</tr>
<tr>
<td>Heavy Clay
(zware klei)</td>
<td>Very vulnerable to swelling, changes in soil strength, and dispersion when exposed to salt.</td>
<td>Very susceptible to drought and very slow to recover.

smearing and compaction under wet conditions.</td>
<td>Susceptible to drought and very slow to recover.

smearing and compaction under wet conditions.</td>
</tr>
</table>

6. Conclusions and recommendations

The aim of this project was to present insights on the process of soil ageing in levees to the commissioners of POV Dijkversterking met Gebiedseigen Grond. To achieve this aim, the soil ageing process in levees and the impact on the levee stability has been determined. Subsequently, the projected climate change in 2050 has been investigated. Penultimately – but most importantly – it has been identified how levees in the Netherlands are affected by soil ageing processes and climate change. Lastly, it has been determined which adaptation strategies could be applied to keep the levees stable and if local (i.e. Dutch) soils could be used for these strategies. This topic will be addressed to in the recommendations.

This report focused on the following soil ageing processes in levees: ***Shrink-swell processes***, ***soil salinization, vegetation in soils***, ***and soil organic matter processes.***

- ***Shrink-swell processes*** are mainly driven by the clay content, organic matter content, and moisture content determined by meteorological factors and vegetation. Soils shrink when they get dry and swell when they get wet. Problems due to shrink-swell processes could lead to piping, internal erosion, slope instability, and serviceability failures in levees.
- **Salinization** has a particularly large influence on smectite clays. This process might reduce the shear strength of the clay since it lowers the amount of pore water required to make the clay flow. However, some studies reported higher compressibility and shear strength of the same type of clay when salt is injected in the pore fluid.
- ***Vegetation*** is at risk of diversity loss by changes in water and nutrient availability. With a decrease in diversity the erosion protection from vegetation decreases.
- ***Soil organic matter processes*** are mainly driven by the amount of organic matter in the soil. It can make levees water repellent and limit erosion by gluing soil particles together. When organic matter oxidates, levees may become weaker.

In all four climate scenarios for 2050, the yearly average temperature in the Netherlands will increase. Moreover, the annual precipitation will increase in all climate scenarios for 2050. Higher moisture contents in the air also result in more heavy rainfall. Extreme precipitation increases in both winter and summer. Although the average yearly precipitation increases, precipitation shortage in the grow season (April-September) increases in every scenario. This apparent contradiction can be explained by the large increase in rainfall during winter, while the summer will very likely experience a strong increase in droughts towards the year 2050. The summers of 2018, 2019 and the current spring drought of 2020 are perfect examples of how droughts are more likely to occur in the near future. Although climate scientists argue that the G-scenario (RCP4.5) is more likely than the W-scenario (RCP8.5), both scenarios pose a threat to the strength of soils in dikes.

The influence of projected climate for 2050 on soil ageing processes and levee stability

Climate change could influence all described soil processes. Therefore, the changes in soil processes caused by climate change will affect the levee stability. For **shrink-swell processes**, an expected increase in droughts and increase in temperature in the Netherlands are very likely to cause an increase in soil shrinking, soil desiccation and soil cracking. These processes could lead to an increase in problems regarding piping, internal erosion, and slope instability for existing levees. For new levees, this could lead to serviceability failures and additional costs. Besides, an increase in extreme precipitation could intensify above mentioned problems. Sea level rise could induce **salinization** in levees further inland, especially in combination with the expected droughts. Introduction of sodium ions in levee soils could impose swelling, increased erodibility and decrease in soil strength. **Vegetation** on levees is also affected by an increase in droughts and extreme precipitation. As droughts in the Netherlands become more prevalent, it is to be expected that fall out of plant species also becomes more common, leaving the vegetation cover compromised. For **soil organic**

matter processes, the direct impact of climate change is the increase of organic matter oxidation rates due to droughts and higher temperatures, which will shrink soil in levees irreversibly. Moreover, a lower organic matter content makes coarse grained soils less resistant to erosion. However, the effect of less present organic matter on swelling/shrinking in clays is variable.

A strong interlink between the four described soil processes has been found. Mainly the influence of an increase in droughts could cause some synergistic processes. The vegetation density could be reduced by droughts, causing a decrease in the stability of levees. At the same time, the water demand of vegetation during droughts will increase, causing an increase in the water deficit. This could lead to enhanced problems regarding shrink-swell processes. Salinization in the form of sodium chloride could reduce the swell capacity of clay soils. This process would not allow to let the cracks restore.

Recommendations for adaptation strategies and further research

- **Initiate in-depth research on bio-activity and fauna in soils under different climate scenarios.** The influence of climate change on bio-activity and fauna in soils is rather unknown as insufficient research appears to have been done. However, existing cracks due to the shrinkage of clay soils can be expanded by the animals, worsening the cracks in the levee. Due to the expected increase of droughts in the Netherlands and thus soil desiccation and cracking, animals will enhance and connect existing cracks more easily. This could have major implications for levee stability. Therefore, research regarding climate change and bio-activity in levees are necessary to fully understand the influence of bio-activity.

- **Initiate in-depth research on the the potential treatment with chemical products could help to improve soil stability in levees.** A possible improvement to levees could be lime treatment. Lime is a product obtained by calcination of calcium carbonate. It can be in the form of quicklime (CaO) or hydrated lime ($Ca(OH)_2$) (Herrier et al., 2012). Currently, it is mainly used for platform construction, airports, railways, and roads. The interest of the levee community with regard to this technique is growing. Positive results in levees regarding lime treatment have been observed at both laboratory and on site. It has been found that lime treatment improved the resistance to surface erosion, resistance to internal erosion, and mechanical strength (Herrier et al., 2019). Therefore, it is worth to study the possibilities regarding lime treatment in depth, as it could contribute to the stability of the levees in the Netherlands. However, negative side is that limestone cannot be found in most local Dutch soils.

- **Add mineralogy of clays in current clay classification to assess clay swelling and dispersion.** Currently, engineers categorize clays according to measured mechanical properties. However, 2:1 (e.g. smectite) clay minerals, are more vulnerable to alteration of their mechanical properties such as swelling and dispersion through hydration and salinization than 1:1 (e.g. kaolinite) clay minerals. Also, interactions of minerals with salt and organic material modify this behaviour. In practice, it is difficult to assess the sensitivity of minerals to clay swelling and dispersion, based on only three quality classes. Adding smectite content into the clay classification scheme could be a good addition.

- **Implement a more diverse use of seeds in levee vegetation.** It might be worthwhile to consider using seed mixtures that contain more diverse and more drought resilient plant species, as the climate keeps shifting, to bolster drought resistance. Complete cover might take longer to form, but the vegetation cover would be more resilient in the future. It might also be necessary to re-assess whether heavy clay remains the most resilient material for levee masks considering the threat of a deteriorated vegetation cover.

- **Set the main focus on droughts for the future.** Where the main focus regarding levees used to be on flooding, droughts are getting and need to get more attention to assess danger of levee failure. Clay burst in levees during dry spells are already a serious problem for water authorities since the dry summers of 2018 & 2019. These bursts have been monitored. However, In the most likely climate scenario with more frequent droughts, clay burst due to shrink-swell behaviour and clay dispersion due to salinization will be an increasing problem and could make Dutch levees vulnerable. Suitable solutions for this are not found yet. Therefore, further research regarding the effects of drought on multiple soil ageing processes and soil properties in levees is necessary.

- **Initiate collaborations with French levee engineers and soil experts.** As the projected climate for the Netherlands in 2050 will be comparable to the current climate of southwestern France, it could be of importance to collaborate with French levee engineers and soil experts. It is possible that they can provide solutions and information about how to cope with droughts and heats. Although it is very likely that most of the levees are constructed on different soil and material, their knowledge could be of major importance to cope with future droughts regarding levee stability in the Netherlands.

- **Initiate research on which soil ageing processes are the most important.** The influence of the described soil ageing processes on shear strength and erodibility of levees are difficult to quantify and are location specific. Different processes are dominant in sand, clay and silt. To obtain a sufficient amount of quantitative data for these processes, multiple researches on multiple locations with different climates should be conducted. However, it is uncertain how relevant every soil process under different climate scenarios is. Before quantifying the processes, it is necessary to determine which of the four soil ageing processes contains the highest probability for levee failure under different climate scenarios.

- **Initiate research on how to stimulate the use of local soils.** Many civil engineers and levee projects aim for utilising local soils for the construction or maintaining for levees. Exceptions can be made if suitable soils from other places are cheaper or if the environmental impact of using local soil is high. However, as long as the design of a levee is good, local soils could almost always be used for the construction of a levee (Bruin & Rookus, pers. communication). The aforementioned strategies, such as lime treatment and seed mixtures among others, could be implemented to improve the local soils. Therefore, local soils could be made more suitable and could reduce construction or maintaining costs. In addition, more soil knowledge and the quantifications of the soil ageing processes could be used to decrease the margin of error within levee stability regarding soils. This could for instance make a local soil suitable enough for a project while initially it was not suitable yet, and therefore could reduce construction costs. However, multiple researches on specific locations with a different climate should be conducted to get the full quantifications.

- **Improve collaboration between civil engineers and soil experts.** During this study it has been found that collaboration between civil engineers and soil experts could have a major contribution to the stability to levees. The commissioners of POV dijkversterking were aiming for the connection between the civil engineering expertise and the soil expertise from Wageningen. The goal of this project was to present insights on the process of soil ageing in levees to the commissioners. Civil engineers sometimes lack knowledge regarding soil ageing processes in levees. This report gave a brief overview of some underexposed soil ageing processes that could influence levee stability regarding climate change. It could be used as a start towards further collaboration between civil engineers and soil experts. Soil experts could give more information regarding the mentioned soil processes – but also other soil processes – and soil mechanics in levees and could help improve levee stability. Civil engineering expertise remains the most important factor regarding levee construction and maintenance. However, collaboration with soil experts could improve processes regarding climate change and soil in levees. Therefore, it could be of major importance to enhance collaborations with soil experts to improve the levees.

- Initiate in-depth further research in response to this report**. This study could be seen as an exploratory** study in which the soil processes have been described in a more general way. This initiated new questions regarding the effects of climate change on soil ageing processes in levees. All four soil ageing processes should be researched more in-depth, especially in combination with droughts. It has been determined that droughts are very likely to be – apart from sea-level rise – the main future concerns regarding levee stability. Currently, no solutions have been found. Therefore, we propose further in-depth research to be conducted on the effects of increasing droughts on the four soil ageing processes in levees.

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Appendix

Over the course of this project a series of six interviews were carried out to gain information and a general understanding. The interviewees were a mix of soil and levee experts. Because a full transcript of the interviews would be too extensive and a summary might misrepresent the ideas of the interviewees, only the main questions are included below. Because the interviewees were all Dutch, the questions were asked in Dutch and will be written down as such.

Interview 1

Date: 22-04-2020

Capacity: Soil expert; senior lecturer WUR

Questions:

Klimaatverandering in Nederland zorgt voor verschillende dingen: Drogere zomers, nattere winters, meer jaarlijkse neerslag, warmere temperaturen en extremere neerslag en langere periodes van droogte.

Wat doen al deze processen met de bodem als je kijkt naar de cohesie, doorlaatbaarheid en schuifsterkte (en andere relevante dingen voor dijken)? Vooral de afwisseling van droogte met extreme neerslag lijkt ons een uitdaging.

Hoe verschillen deze processen voor clay, silt en sand? E.g. Welke bodems zijn relatief ongevoelig voor droog/nat afwisseling, welke wel?

Naast uitdroging, supersaturatie van poriën en verzilting, zijn er meer klimaatgerelateerde processen die een invloed hebben op de kracht van dijken? Welke verouderingsprocessen zijn relevant op een tijdschaal van decennia (nu tot 2050)?t

Kan clay leaching effect hebben op de tijdschaal van decennia?

zou organisch materiaal in bodems anders dan veen invloed kunnen hebben op de schuifsterkte?

Valt invloed van organismen ook onder bodemveroudering? Zo ja, is er op dit gebied verandering te verwachten bij de geprojecteerde klimaatverandering?

In hoeverre is verzilting door zeespiegelstijging van toepassing op landinwaartse dijken?

Wij vinden het tot zover lastig om goede bronnen te vinden waar de combinatie van klimaatverandering en verandering in bodemprocessen (veroudering, cohesie, doorlaatbaarheid en schuifsterkte) goed onderzocht is. Zijn er papers/boeken waar dit soort informatie of tabellen in staan? Is er überhaupt kwantitatieve data, of is het in het grote lijnen vooral nog gebaseerd op kwalitatieve data?

Interview 2

Date: 23-04-2020

Capacity: Soil expert; senior lecturer WUR

Questions:

Klimaatverandering in Nederland zorgt voor verschillende dingen: Drogere zomers, nattere winters, meer jaarlijkse neerslag, warmere temperaturen en extremere neerslag en langere periodes van droogte.

Wat doen al deze processen met de bodem als je kijkt naar de cohesie, doorlaatbaarheid en schuifsterkte (en andere relevante dingen voor dijken)? Vooral de afwisseling van droogte met extreme neerslag lijkt ons een uitdaging.

Hoe verschillen deze processen voor clay, silt en sand? E.g. Welke bodems zijn relatief ongevoelig voor droog/nat afwisseling, welke wel?

Naast uitdroging, supersaturatie van poriën en verzilting, zijn er meer klimaatgerelateerde processen die een invloed hebben op de kracht van dijken? Welke verouderingsprocessen zijn relevant op een tijdschaal van decennia (nu tot 2050)?t

Kan clay leaching effect hebben op de tijdschaal van decennia?

zou organisch materiaal in bodems anders dan veen invloed kunnen hebben op de schuifsterkte?

Valt invloed van organismen ook onder bodemveroudering? Zo ja, is er op dit gebied verandering te verwachten bij de geprojecteerde klimaatverandering?

In hoeverre is verzilting door zeespiegelstijging van toepassing op landinwaartse dijken?

Wij vinden het tot zover lastig om goede bronnen te vinden waar de combinatie van klimaatverandering en verandering in bodemprocessen (veroudering, cohesie, doorlaatbaarheid en schuifsterkte) goed onderzocht is. Zijn er papers/boeken waar dit soort informatie of tabellen in staan? Is er überhaupt kwantitatieve data, of is het in het grote lijnen vooral nog gebaseerd op kwalitatieve data?

Interview 3

Date: 24-04-2020

Capacity: Coordinating specialist advisor Rijkswaterstaat; Author Levee handbook

Questions:

Waarom is er geen nadruk op de invloed van bodemveroudering op de sterkte van dijken in het Levee Handbook? Is dat omdat er geen kennis van is of omdat het irrelevant is. Zijn er nog meer processen binnen het kader van klimaatverandering waar weinig van bekend is bij constructie(falen) van dijken?

Hoe worden bodemprocessen meegenomen bij dijkversterkingen?

Wordt er in Zuid-Europese landen gebruik gemaakt van andere materialen voor de constructie van dijken dan in Nederland? Zijn er überhaupt processen/problemen waarvan de Nederlandse dijk-experts kunnen leren van bijvoorbeeld Franse of Italiaanse dijk-experts?

Zijn er in Nederland dijken die oud genoeg zijn om te kunnen stellen dat de samenstelling is veranderd over die tijd?

Bij zeedijken speelt zout water een rol in de stress/erosie op de dijk, wat is hier het verschil in ten opzichte van rivierdijken? In hoeverre is verzilting door zeespiegelstijging van toepassing op landinwaartse dijken?

Is regen een relevante eroderende factor voor dijken?

Welk onderdeel van een dijk is het meest gevoelig voor verouderingsprocessen?

Welke verouderingsprocessen zijn relevant op een tijdschaal van decennia?

In hoeverre is verzilting door zeespiegelstijging van toepassing op landinwaartse dijken?

Welke bodems zijn relatief ongevoelig voor droog/nat afwisseling, welke wel?

Naast uitdroging, supersaturatie van poriën en verzilting, zijn er meer klimaatgerelateerde processen die een invloed hebben op de kracht van dijken?

Interview 4

Date: 29-04-2020

Capacity: Policy advisor water safety waterschap Noorderzijlvest; contact person ommelanderzeedijk

Questions:

De Ommelanderzeedijk bestaat uit een combinatie van zand en klei (en asfalt). Hoe is de zeedijk precies opgebouwd? Heeft de core of juist de deklaag weer een hogere samenstelling van zand of juist klei?

We hebben gelezen dat de Ommelanderzeedijk zo gebouwd is dat het tegen aardbevingen van 5.0 op de schaal van Richter kan. Hoe is de dijk aardbevingsbestendig gemaakt? Hebben aardbevingen grote invloed op de bodem en sterkte van de dijk?

Klimaatverandering in Nederland zorgt voor verschillende dingen: Drogere zomers, nattere winters, meer jaarlijkse neerslag, warmere temperaturen en extremere neerslag en langere periodes van droogte. Wat doen al deze processen met de bodem als je kijkt naar de cohesie, doorlaatbaarheid en schuifsterkte voor een combinatie van zand- en kleibodem?

Welke bodems binnen de zeedijk zijn relatief ongevoelig voor droog/nat afwisseling, welke wel? Naast uitdroging, supersaturatie van poriën en verzilting, zijn er meer klimaatgerelateerde processen die een invloed hebben op de kracht van de Ommelanderzeedijk en dijken in het algemeen?

Heeft u bestanden en data van de Ommelanderzeedijk beschikbaar die wij zouden kunnen inzien?

Is verzilting bij zeedijken een probleem? Zo ja, hoe houden jullie daar rekening mee?

Hebben jullie te maken met dieren die gangen graven in dijken? Zo ja, hoe gaan jullie daar mee om?

Interview 5

Date: 18-05-2020

Capacity: Technical manager realisation waterschap Vallei en Veluwe / Policy staff member water safety; contact persons Grebbedijk

Questions:

Hoe is de rivierdijk precies opgebouwd? Heeft de core of juist de deklaag weer een hogere samenstelling van zand of juist klei?

Heeft u bestanden en data over de structuur van de Grebbedijk beschikbaar die wij zouden kunnen inzien?

Klimaatverandering in Nederland zorgt voor verschillende dingen: Drogere zomers, nattere winters, meer jaarlijkse en meer extreme neerslag, hogere temperaturen. Wat doen al deze processen met de bodem als je kijkt naar de cohesie, doorlaatbaarheid en schuifsterkte voor een combinatie van zand- en kleibodems?

Welke bodems binnen de rivierdijk zijn relatief ongevoelig voor droog/nat afwisseling, welke zijn wel gevoelig? Naast uitdroging, supersaturatie van poriën en verzilting, zijn er meer klimaatgerelateerde processen die een invloed hebben op de kracht van de Grebbedijk en dijken in het algemeen?

Wordt er rekening gehouden met klei mineralogie (smectite/montmorillonite, kaolinite, illite) bij het keuren van een klei? Zo ja welke hebben de voorkeur en waarom?

Is verzilting bij rivierdijken een probleem? Zo ja, hoe houden jullie daar rekening mee?

Hebben jullie te maken met dieren die gangen graven in dijken? Zo ja, hoe gaan jullie daar mee om?

Interview 6

Date: 20-05-2020

Capacity: PhD student WUR

Questions:

Wij hebben ondervonden dat bijvoorbeeld in het levee handbook en over het algemeen bij de constructie van dijken niet of nauwelijks rekening is gehouden met bodemprocessen. Is dat omdat er geen kennis van is of omdat het irrelevant is? Zijn er nog meer processen binnen het kader van klimaatverandering waar weinig van bekend is bij constructie(falen) van dijken?

Welke bodemprocessen in dijken zijn volgens jou nog het meest onderbelicht en zouden cruciaal kunnen zijn binnen het kader van klimaatverandering in Nederland?

Denk je dat er meer samenwerking zou moeten plaatsvinden tussen bodemexperts en de civiele techniekexperts om de houdbaarheid van dijken te verzekeren? Hoe ervaar jij dit binnen jouw expertise en omgeving?

Bij zeedijken speelt zout water een rol in de stress/erosie op de dijk, wat is hier het verschil in ten opzichte van rivierdijken? In hoeverre is verzilting door zeespiegelstijging van toepassing op landinwaartse dijken?

Bij verzilting van (montmorillonite)kleien staat in literatuur dat de plasticiteit veranderd en dat de vloeigrens kan afnemen van zo'n 400% naar 150%, wat betekent doet dit met het gedrag van de klei?

Tegelijk is er sprake van toename in schuifspanning (shear strength), dit lijkt tegen te spreken. Weet jij daar meer over?