pov dijkversterking
met gebiedseigen grond

Incorporating the erosion sensitivity of local soils in a levee safety analysis

An evaluation of internationally available methods

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Preface

This report has been written for a technical audience with a basic understanding of geotechnical principles and the principles of erosion. The report serves to provide a current overview of the accepted available knowledge on the erosion of construction material in levees, and how to account for this in levee safety analyses using breach models. The information outlined in this report serves to benefit the use of local construction materials for levee construction.

Contents

1. Introduction

The Project titled “Exceeding investigation of levee reinforcement with local soil” (Projectoverschrijdende verkenning van dijkversterking met gebiedseigen grond) (POV DGG) aims to facilitate the use of local soil in levee design. The development of tools by the POV DGG to facilitate this will be aligned with the development of the legal instruments for designing and evaluating levees, developed as part of the BOI (Beoordeling en Ontwerp-instrumentarium). The POV DGG aims to identify (inter)nationally widely accepted and validated methods, which could be transferred into national tools with a design status which facilitate the use of local soil in levee construction.

This report aims to provide the POV DGG with an inventory of the available established international knowledge with respect to erosive properties and erosion resistance. Feedback obtained from end-users during webinars organized by the POV DGG, has been adopted in this second version of the report. In terms of content, the report covers only one aspect of how soil properties affect levee design, and what instruments are available to account for erosion in levee safety analyses. Other reports developed as part of the POV DGG deal with the impact of other failure mechanisms. The report finishes with recommendations on how the current knowledge could be extended to facilitate the design of levees with local soil. This report thereby focuses on qualitative descriptions of the different approaches and thereby only mentions quantitative prediction methods in case this also serves an indicative purpose.

The research into the field of erosion has led to numerous predictive formulae. The author aimed to evaluate only those approaches for which reasonable consensus exists. Despite this consensus the author attempted to remain critical of the approaches. Equations and erosion parameters, that are mentioned in this report, have been peer reviewed and/or have been adopted in several commercially available models. References are provided with the information such that readers may provide themselves with more details. The report also comments on how the available methods fit within the “Story of the Levee” concept, which is one of the 5 objectives of the (Evaluation and design instrument) BOI and in underlying the Knowledge development programme (KvK) of Rijkswaterstaat WVL. The report has been written with the aim of the POV DGG in mind and aims to provide a technical framework for evaluating erosive properties of soil.

Chapter 2 of this report discusses the framework within which erosion relations have been applied internationally. Chapter 3 discusses which proven methodologies are available to determine the erosive properties of soils, how these depend on soil properties, and what weaknesses and strength the methods have. Chapter 4 subsequently discusses a method of categorizing the different measurements of soil erodibility and provides an overview of the current level of knowledge (inter)nationally. Chapter 5 contains a discussion on how to utilize small-scale tests to facilitate the used of local soil in levee designs. The discussion leads to the recommendations made in Chapter 6. The author acknowledges that the use of erosion models for safety assessment of levees is still in its infancy. The aim is therefore not to focus on what gaps in knowledge are occurring, although these certainly are addressed, but is to focus on how the available methods can be used.

2. Incorporating erosion in levee safety

For the design of levees, the POV DGG aims to develop tools which can be used to design and evaluate levees based on the "Story of the levee" concept, which underlies the development of instruments as part of the BOI programme. Instead of focusing on when a single failure mechanism occurs, the story of the levee concept considers a levee to have failed once a full breach has formed. Several pathways, whereby failure mechanisms interact, can lead up to a levee breach. One vitally important process thereby is erosion as it forms a binding factor between failure mechanisms. A breach model, which translates the erosion resistance into a failure probability is essential when aiming to account for the erosion resistance. This chapter therefore first focuses on the formation of a breach in levees and the generally well accepted breach models available to model this.

In the Netherlands, UK, France and USA, breach models have been developed to evaluate the subsequent steps along which levees breach due to wave impact, overflow or piping. The development of breach models has pushed research into the erosive properties of dam and levee material. Empirical (Verheij, 2003), semi-empirical (Fread 1984; Macchione, 2008), and process-based breach models. (Visser, 1998; Mohamed, 2002; Zhu, 2006; Van Damme et al., 2012; Wu, 2013; Davison et al., 2013; Klein Breteler, 2019) can be distinguished. The aim of process-based breach models, to evaluate the full chain of events that leads to a breach, in principle aligns well with the research into failure pathways along the principle of the "Story of the Levee". However, the effectiveness of using process-based breach models to evaluate failure pathways is limited. Currently no process-based breach models are available that can evaluate how a levee cross section erodes after a geotechnical failure has occurred. Neither do breach models check for geotechnical stability of, a by erosion affected cross-section. Commercially available process-based models focus on modelling the breach due to wave impact, overflow and piping. In the case of wave impact, or overflow, the generic erosion profile is assumed to have a specific shape consisting of line elements. In the case of piping, these models assume that, initially a full pipe has already formed (Mohamed, 2002; Van Damme et al., 2012). Simplistic assumptions have thereby been used to evaluate when the pipe roof collapses. Academic models have been developed to simulate the process of breach formation due to wave overtopping (D'Eliso, 2007). Breach models are therefore limited in the processes that are included.

Breach models inherent descriptions of failure by wave impact, piping or overflow (Mourik, 2017; Van Damme, 2012), are based on an assumed single dominant failure pathway. This translates in a pre-described time dependent change in erosion profile. The rate of erosion thereby only determines the rate at which profiles change its shape. Once a global erosion process is pre-defined by a user, the general breach formation process is assumed to be independent of the levee material. The location where erosion initiates is thereby often hard coded. In the case of overflow, or wave overtopping, erosion is assumed to start at the landside slope, which retreats towards the waterside slope due to erosion. In reality however, large-scale experiments (Hassan & Morris, 2009) have shown that geotechnical processes, hydraulic processes, and erosive processes all affect each other. Accounting for all these processes using specific geotechnical, hydrodynamic and erosion models has been too challenging thus far. Figure 1 depicts a generic breach hydrograph for a case of failure induced by overflow. Here Q denotes the breach discharge Before T_1 no overflow occurs over the levee. Between T_1 and T_2 overflow has induced erosion of the levee material but the levee still retains its function. Between T_2 and T_3 erosion has reached the waterside slope. During this short amount of time the breach deepens, and starts to widen. At T_3 a full breach has formed over the full height of the levee, and between T_3 and T_4 the breach discharge continues to increase as the breach widens. Only when the water levels reduce, the flow through the breach reduces. Consequently, the stage between T_1 and T_2 is indicative of the residual strength of levees. The situation at T_4 is however the most damaging. Breach models are often evaluated on the basis of how well they predict the peak discharge and time of occurrence of the peak discharge and not on their basis of how well they simulate the entire breach initiation and formation process.

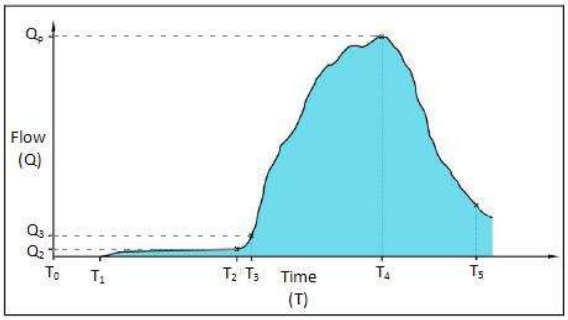

Figure 1: Generic breach hydrograph

Despite the limitations of breach models to account for the interaction in hydraulic, geotechnical and erosive processes, important lessons learned from the research behind breach model development align with one of the objectives of the POV DGG to include erosion processes in the safety assessment of levees. Models for wave impact, overflow, and piping, though not perfect, have thereby been developed to serve as a platform for use in levee designs. Provided that model uncertainties are sufficiently accounted for, these models are applicable for levee designs. For that reason, the following sections outline how breach models simulate the erosive processes during the initial stages of breach formation.

2.1 Simulating erosion due to overflow

The sections below outline how breach models account for the erosion processes in Breach Formation Stage T_1 to T_2 . When a flood embankment overflows, either headcut erosion processes or surface erosion processes have been witnessed to drive breach formation.

2.1.1 Failure of the grass cover

Wave overtopping and overflow experiments performed on grass covers in the Netherlands indicate that grass covers are more erosion resistant than the layers below the grass cover. The degree of erosion resistance is thereby assumed to be a function of the structure of the grass cover, the type of subsoil, and the type of loading. Grass grows best on soil with an open structure. Consequently a grass cover on a dense erosion resistant clay layer may perform worse than a grass cover placed on a more open, less erosion resistant clay layer. In the Netherlands, a distinction is made in erosion resistance between grass covers on a clay layer and grass covers on a sand layer. Thereby a distinction is made between a closed grass cover, an open grass cover, of a fragmentary cover. In the UK, the CIRIA 116 curve distinguishes three quality types of grass cover. The quality of the grass cover therefore significantly affects the level of erosion resistance it offers. It should be noted that the presence of burrowing animals also significantly affect the onset of failure of grass covers. However this influence has not yet been quantified. Due to the significant influence, it is recommended to account for the erosion resistance of grass when assessing levee failure probabilities.

2.1.2 Headcut erosion

When clay or silt levee material is subjected to significant overflow, headcut erosion sets in. Headcut erosion results in a cascading flow pattern (See Figure 2). When water begins to cascade, the bathymetry is represented by a series of steps containing horizontal and vertical plateaus. The flow separates from the bed at the transition from a horizontal to a vertical plateau until it reattaches at the lower lying horizontal plateau (see Figure 2).

The erosion process is modelled by assuming that horizontal plateaus erode downwards, and the

Figure 2: Headcut erosion processes during overflow (After Hanson, 2005)

vertical plateaus retrogressively erode in horizontal direction through the levee (see Figure 2) This process is described as headcut erosion. Especially for clayey soils it is well accepted that the levee will erode due to headcut erosion. For levees with a clay cover on the waterside slope, and fine sand on the landside slope, headcut formation has also been observed during overflow. Moreover, this process was witnessed during large-scale wave overtopping experiments on levees with a clay cover and sand core. In both cases, the core material of the levee was not yet saturated at the onset of the erosion. The location where headcut erosion initiates is often unknown as it is determined by local irregularities in the slope profile, or local weak spots. When modelling the headcut erosion process in breach models, it is therefore often assumed that headcuts initiate at the worst possible location along the landside slope, which is located where the crest and landside slope meet.

2.1.3 Surface erosion

Medium to course sands are assumed to erode due to the surface erosion process. In the case of surface erosion, the flow is assumed to remain attached to the breach surface, causing for diffusion of the cross sectional breach profile, and simultaneous retreat of the waterside slope to the landside slope, due to the increasing rates of erosion with the increase in bed slope gradient (see Figure 3)

Figure 3: Surface erosion process during overflow (Visser, 1996)

2.1.4 Determining the dominant erosion process

Whether a levee erodes due to the headcut erosion process (see Figure 2) or the surface erosion process (see Figure 3) is likely to be dominated by small-scale geotechnical processes. If shallow shear failures occur in sand, then headcuts are likely to be prevented from occurring. When headcut erosion or when surface erosion occurs is however

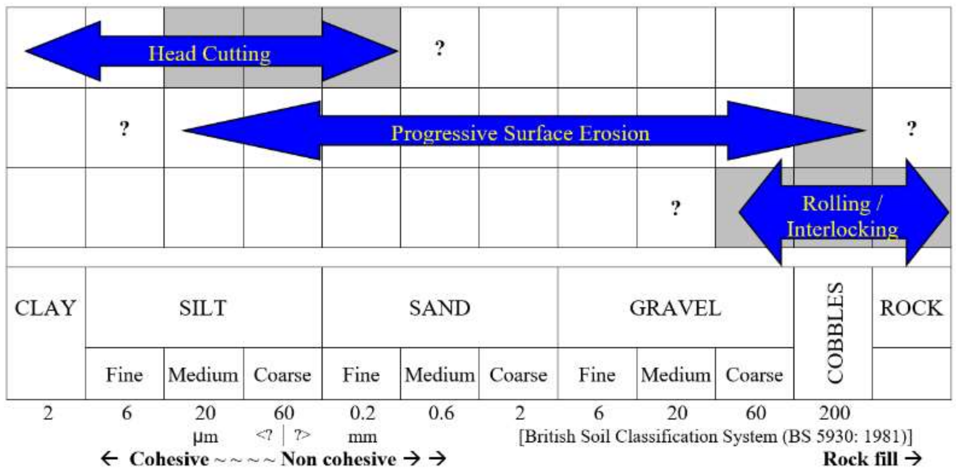

Figure 4: Transition in erosion process from headcut erosion to surface erosion (After Morris, 2011)

insufficiently understood and is considered one of several remaining challenges in breach modelling. A generic accepted overview is given by Morris (2011) (see Figure 4). In all breach models, the type of erosion is either incorporated in the underlying assumption of the model, or needs to be user defined. Transitions from one regime to the other cannot be simulated yet.

Breach formation is governed by a complicated interaction between geotechnical, sedimentary, and hydrodynamic processes. Academic initiatives are planned in the UK to develop breach models by combining geotechnical models, hydrodynamic models, and erosion relations. A challenge is validation of these models. The hydrodynamic processes are volatile (see Figure 3), making the determined stresses that act on the levee highly uncertain. Predicting the corresponding erosion processes and other failure mechanisms therefore also becomes highly uncertain and challenging. The interaction between processes also generates significant scaling problems. Small-scale experiments could be useful to study specific processes during breach formation but do not offer a proper representation of a full breach formation process. Due to the complicated interaction of processes, and uncertainties in how partially saturated soil reacts, various failure scenarios are probable. Provided that the individual process can be modelled well, then probabilistic techniques, like Monte Carlo, could be used to evaluate the likelihood of each failure scenario. The difficulty to monitor all the processes during experiments does make it highly challenging to validate breach models.

Figure 5: Impression of the complicated hydrodynamic conditions during breach formation

2.2 Simulating erosion due to wave impact

Due to repeated wave impacts on the waterside slope, a clay dike cover can start to erode whereby a mildly sloping terrace and a steep cliff face form (see Figure 6). This process has been described in a commercially available breach model (Klein Breteler, 2019). According to the model, and in line with observations, the terraced slope slowly erodes downwards, while the cliff slope proceeds through the levee. The assumed steepness of the cliff is 1:1. This steepness is based on the visual observation that soil above a steeper cliff is undermined and becomes unstable. Consequently, the inherent model assumptions describe both the erosive processes and geotechnical processes. The speed at which the terraced slope erodes downwards reduces when the terrace is submerged. With erosion of the cliff, the terraced section causes waves to break before reaching the eroded cliff face. Consequently, the rate at which the cliff face erodes, decreases. Nevertheless, the cliff face continues to erode due to the process of wave run-up. The speed at which soil erodes is related to the significant wave height, wave steepness, slope angle, and model coefficients for the different soil types and terrace level, which are related to the soil erodibility. For the Grebbedijk a levee safety analysis, which accounts for the erosion resistance of levee material, has already been performed with this model (Klein Breteler, 2019).

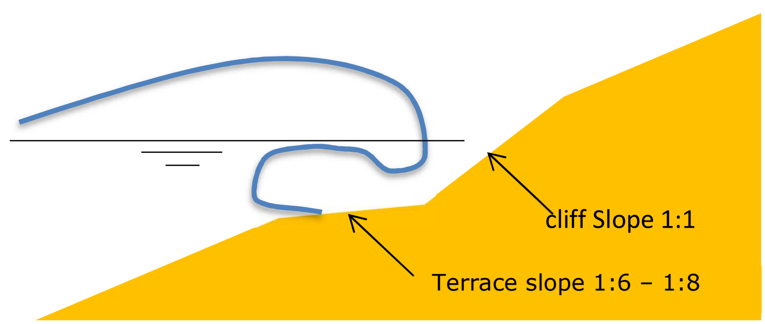

Figure 6: Assumed shape during breach formation by wave impact

2.3 Conclusions of the breach modelling approach

Despite the fact that little is known on the exact processes along which levees erode, the breach models outlined in Sections 2.1 and 2.2, provide a platform to include erosion characteristics of soils in levee design. The user of the models should however be aware of their limitations and shortcomings, and apply these models with care. The range of uncertainty surrounding these models remains significant as only one dominant failure pathway is assumed to dominate the breach formation process. This failure pathway is not necessarily the critical failure pathway. Despite the limitations of the models, useful lessons could be drawn from this approach namely:

1. In the case of homogeneous clay and fine silt levees, the process of erosion due to overflow is dominated by headcut erosion.
2. In sandy material, the type of erosion that occurs during overflow depends on several factors and is therefore uncertain. Levees consisting of course sand erode by surface erosion.
3. In the case of overflow, the location where erosion initiates is often uncertain.
4. The uncertainty surrounding the prediction of the breach formation is greater than purely the uncertainty surrounding erosion processes.

3. Quantifying erosion rates

Breach models form a platform needed to account for the erosion resistance of soil in levee safety analyses. The accuracy of the models, and analyses, depends on the accuracy with which the erosive properties of soil can be determined. Research incentives therefore focus on accurately predicting the rate of erosion. Most breach models, include erosion relations which resemble the form:

$$E = \begin{cases} K(\tau - \tau_c)^\alpha \text{ for } \tau > \tau_c \\ 0 \text{ for } \tau \leq \tau_c \end{cases} \qquad \text{1a}$$

Where *E* [m/s] denotes the erosion rate, *K* denotes the soil erodibility, τ denotes the bed shear stress, and τ_c the critical bed shear stress. The units for the soil erodibility depend on the power of coefficient α. Large research programmes in the USA and UK have focussed on improving the way in which the critical shear stress and the soil erodibility can be determined for various soils. Briaud et al. (2019) presented relations between the erosion rate and shear stress for various types of soil. On the basis of these relations, for various soil types, a first estimate for the soil erodibility could be derived.

3.1 Accounting for grass erosion in failure models

In the Netherlands a cumulative overload method has been developed to evaluate the resistance of grass covers during wave overtopping. The cumulative overload method has a similar structure as Equation 1 and finds its basis in the following formula:

$$D = \sum (u^2 - u_c^2)t \qquad \text{1b}$$

where *D* denotes a damage number [m^2/s] and u [m/s] is a wave velocity at the dike slope.
The stress τ is believed to be proportional to u^2. Consequently, the critical shear stress could also be expressed in terms of a velocity. The time t denotes the time over which the stresses exceed the critical stress. The wave velocity of an overtopping wave is initially maximum and after that rapidly decreases. It has therefore been hypothesized that the influence of time *t* is negligible and has therefore been assumed constant leading to formule 1c used in the cumulative overload method.

$$D = \sum (\alpha_m (\alpha_u u)^2 - \alpha_s \, u_c^2) \qquad \text{1c}$$

where α_m, α_u are factors to account for the influence of transitions and flow acceleration, and α_s is a correction factor for the strength in the case of transitions. Please note that the damage coefficient D in Equation 1c now has units [m^2/s^2]. The influence of the factor *K* in Equation 1a, the time *t* and the roughness parameters that relate the velocity squared to the stresses applied on the cover have thereby all been captured in the damage coefficient *D.*

CIRIA published empirical curves for the erosion resistance of grass against overflowing water. These curves account for the fatigue effect of grass (Whitehead et al. 1976). According to these curves, the critical velocity at which a grass cover fails, decreases exponentially with time. In Equations 1b and 1c this fatigue effect is partially captured via the cumulative effect. It should be noted that the critical velocity is dependent on the soil type on which the grass grows. Once the grass cover has failed, erosion sets in according to the processes described in the breach models.

3.2 Accounting for erosion in breach models

Whether the surface erosion or the headcut erosion process dominates breach formation is difficult to predict and is therefore user defined in breach models.

3.2.1 Headcut erosion

Headcut erosion relations presented here for illustrative purposes have been adopted in the simplified headcut erosion model (SIMBA), and the commercially available breach models EMBREA (Davison et al., 2013), and AREBA (van Damme, 2014). The relations are based on the work of Temple et al. (2005). The rate of downwards erosion is determined using Equation 1a. With headcut erosion, the bed shear stresses are related to the normal impact of the water flow and follow from the relation for a plunging jet under the assumption of a low tail water (Temple et al., 2005). The horizontal rate of displacement of the vertical sections of the steps dx/dt is determined via

$$dx/dt = -C(qh_{hc})^{1/3} \qquad 2$$

Where *C* is a headcut coefficient, *q* is the breadth averaged overflow discharge [m^2/s], and h_{hc} is the step height of a headcut, and d_c is the critical depth. The headcut coefficient C is linearly dependent on the soil erodibility *K*. When the soil erodibility decreases by a factor of 2, then the rate of increase in the step height also becomes a factor 2 smaller. Equation 2 indicates that the horizontal retreat of the vertical step face is linearly dependent on *K,* but is also non-linear dependent on the step height h_{hc}. The effect of the prediction of the soil erodibility is therefore even higher on predicting the rate of horizontal retreat of the vertical step faces, than on the downwards erosion of the horizontal step faces.

3.2.2 Surface erosion

Erosion of sand consists of the sum of the deposition and pick-up of sediment from the bed. When the pick-up rate equals the deposition rate, then the erosion rate is zero. In the case of breaching, the deposition rate of particles is often assumed to be negligible. The flow continuously accelerates as it moves along the embankment surface into the polder. The short distance along which the flow picks-up particles is insufficient to reach equilibrium transport conditions. Many breach models also use the Erosion Equation (see Equation 1a) to predict the erosion rates of sand whereby the power coefficient is assumed to be unity. However, also other pick-up relations have been developed for the erosion of sand under high flow velocities. Most of these are empirical. However, Van Damme (2020) derived a purely process-based pick-up relation for sand by solving the momentum balance equations for the process of dilation. Dilation describes the processes of a shear induced change in pore volume. The pick-up relation was validated against flume data by Bisschop (2018) who performed

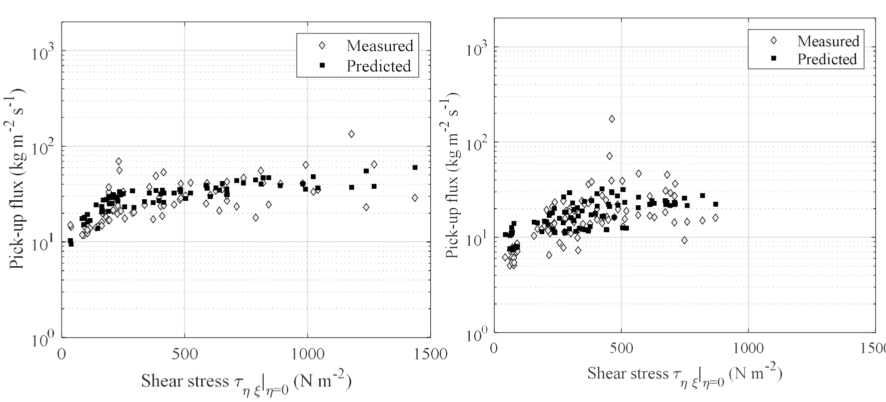

Figure 7: Predictions of the process based erosion relation for sand (After Van Damme, 2019)

flume erosion experiments on different types of sand under flow velocities between 2 and 7 m/s (see Figure 7). Since the relation developed by van Damme (2019) was purely process based, in theory the predictions could be applied to other types of non-cohesive dilatant materials. However, this yet needs to be validated. The results are however indicative of the impact of the degree of compaction on the soil erodibility. It should be noted that the effect of the dilation gives an approximately square root dependency of the erosion rate on the shear stress. Bisschop (2018) noted that this power is likely to be much smaller than 1. In several breach models the erosion rate of sand is also predicted using the erosion equation, whereby the power coefficient α is assumed to be unity. Discussions have recently arisen on the correct value for the power coefficient α in the erosion equation.

3.2.3 Clay erosion by wave impact

In the Netherlands, the research programme WTI -2017 led to predictive formulas for the erosion velocity of a slope of clay due to wave attack. The formulas were developed to quantify the residual strength of levees once the cover layer has failed. In the formula, the rate of erosion is linked to the peak pressure (Mourik, 2017)). The peak pressure has been related to geometric and hydraulic parameters using hydrodynamic models. The erosion relation was validated against Delta Flume experiments with fresh water waves eroding clay and boulder clay (Wieringermeer) with the following characteristics (see Table 1):

Table 1: Soil characteristics of the materials used in the developed wave impact erosion relation (Mourik, 2017)

Test	Oosterland	Ferwert	Wieringermeer	Kruiningen	Perkpolder
Percentage sand	5-15%	10-15%	56%	18%	32%
Percentage organic matter	4-5%	2-7%	1-2%	0.5%	0.4%
Liquid limit	45-65%	40-65%	21-23%	43%	39%
Plastic limit	20-30%	20-35%	14-15%	23%	20%
Plasticity index	20-35%	20-35%	5-8%	21%	19%

Clay was deemed more erosion resistant than boulder clay. One generic erosion relation was developed for both types of clay. Differences in erosion resistance were incorporated via a model coefficient. Mourik (2017) noted that the rate of erosion is linearly dependent on the peak pressure.

The Technische Universität Braunchweigh studied the erosion resistance of clay with and without water filled cracks. They noted that available cracks weaken the stability of clay covers of sea dikes. On a cracked clay cover, hydraulic impact pressures were generated which correspond to wave heights up to 1.2 m. The influence of several parameters was linearly related to an excess boundary stress via the soil erodibility parameter (See Equation 1). Here, the peak impact pressure and the critical stress respectively replaced the bed shear stress and critical shear stress. The power coefficient was set to unity. Nobel (2013) also found a linear relation between the jet pressure and the erosion rate. Consequently, there seems to be international consensus that the erosion rate of clay is linearly dependent on the excess stress.

The accuracy with which breach models are able to represent the breaching process well is largely determined by the accuracy with which the soil erodibility parameter and critical (shear) stress can be determined. For that reason several testing apparatuses have been determined to identify these parameters.

3.3 Testing apparatuses

The following tests have all been applied to derive the Soil Erodibility K and critical shear stress τ_c given in Equation 1a. All tests impose a flow on a soil sample. With exception of the RCT, whereby the shear stresses are measured directly, in all methods the velocity is determined and transferred into a shear stress using empirical relations. The rate of erosion is also measured. After substitution of the bed shear stress and erosion rate in Equation 1a, a critical shear stress τ_c and soil erodibility K are derived. The critical shear stress is thereby either derived directly from measurements of the velocity whereby erosion no longer takes place, or is derived by extrapolating the best linear fit between the measured erosion rates, and the bed shear stresses.

3.3.1 Flume experiments

Tilting flumes have been used to perform erosion experiments on different types of soil as flow velocities up to 2 m/s could be obtained. These flumes could be used to determine the transition from the low velocity erosion regime to the high velocity erosion regime. For higher flow velocities a pressurized flume could be used as shown in Figure 8. Bisschop (2018) performed erosion experiments on different types of sand under high flow velocities using an enclosed laboratory flume with a bypass channel (see Figure 8). Once the flow in the main pipe section was ramped up to the required speed, the flow was redirected over a sand sample located in the bypass channel. Bisschop (2018) repeated this experiment for various flow velocities ranging between 2 and 6 m/s. A radio-active density meter was installed to measure the mixture concentration, conductivity probes were used to monitor the change in bed level, and pressure gauges were used to monitor the pressure gradients over the test section. The flow velocity was measured using an Electro-magnetic flow meter. Based on the measurements the pick-up rate was set out against the bed shear stress τ (See Equation 1a).

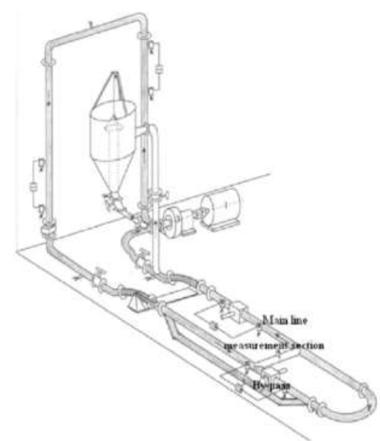

Figure 8: Test setup after Bisschop (2018)

3.3.2 Erosion function Apparatus (EFA)

The EFA (Rook, 2020) operates similarly to other devices like the Sediment Erosion at Depth flume, or the Sediment Erosion rate flume (Briaud, 2019). The erosion rate is determined by inducing a flow in a duct. In the bed of the duct a circular hole is present. In this hole a sample container is placed which is supported by a piston in the bottom. The piston pushes the soil sample in the flow at such a rate that the top of the sample remains flush with the bottom of the duct (see Figure 9). By repeating the experiments for different flow velocities, and therefore shear stresses, different erosion rates are found. Erosion measurements were performed in the range of 0.2 to 6m/s.

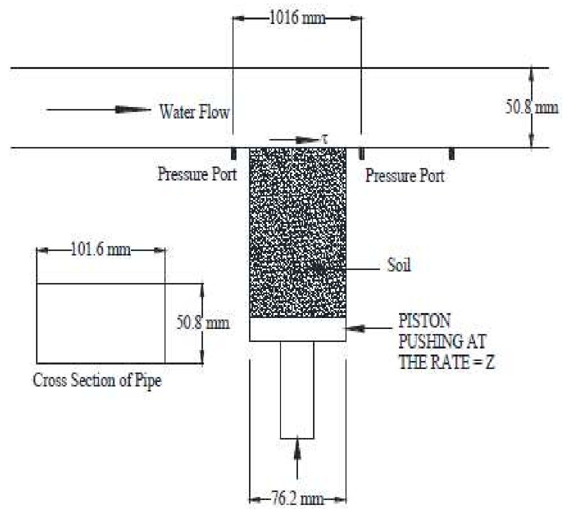

Figure 9: EFA principle (After Briaud, 2019)

Heijmeijer (2019) performed erosion measurements using an EFA type apparatus at Boskalis whereby a sand sample was remained flush with the bed level of a square steel duct. Contrary to the approach of Briaud (2019), Heijmeijer (2019) used a flume which had a square test sample container with a width of 188 mm. Heijmeijer (2019) performed erosion measurements using the same type of sand as Bisschop (2018), for the same range of flow velocities. Heijmeijer found consistently larger pick-up fluxes at the same flow velocity as Bisschop (2019). It seems that a potential disadvantage of the EFA, and similar erosion apparatus, is that besides, mass, also momentum is added to the flow. The momentum balance equation describing the erosion process is therefore different than for the case whereby the bed solely erodes downwards. However, in the case of flume experiments whereby the bed is allowed to erode, the wetted cross section increases with an increase in eroded material. This induces a local deceleration of the flow and subsequent lower erosion rates. It also makes it more difficult to obtain high quality measurements. The addition of momentum by the movement of the piston however appears to lead to an overestimation of pick-up fluxes.

3.3.3 Jet Erosion Test (JET)

During headcut erosion, the flow cascades (See Figure 2). At the base of a cascade the flow is redirected. The momentum transfer between the flow and the bed is in this case higher than in the case of a parallel flow along a flat bed. The JET (Hanson, 1990) aims to reproduce this loading process. In analysing the results of the JET the erosion rate is related to the bed shear stress. The JET was originally designed to be applied to cohesive soils. The standardized JET includes a nozzle with a diameter of 13 mm which is held 22 mm from the soil surface. The standard JET operates at a pressure head of 775 mm water column giving an exit velocity of the water from the jet of approximately 4m/s. With erosion of the soil under the jet, the distance from the nozzle increases, causing for a decrease in shear stresses. The JET can be applied in the lab or in the field. A pin profiler can be used to determine the dimensions of the scour hole. Besides the standard JET also a mini-JET has been developed with a pressure head of 450 mm to 610 mm, and a nozzle diameter of 3.18 mm. Boucher et al. (2019) also developed a large jet, the LJET, which aims at performing the JET on gravel soil with particles in excess of 4.75 mm. The LJET method has been evaluated with nozzle diameters varying from 6.35, 12, and 20 mm. The nozzle diameter did not appear to influence the results significantly. The pressure head could be increased to 800 mm water column during an LJET, thereby giving the same range of exit velocities as the original JET. Besides the JET also a submerged JET was developed. This operates according to the same principles as the normal JET. However the JET exits under water. The bed shear stress follows from

$$\tau = c_f \rho_w u^2 \left(\frac{J_p}{J_i}\right)^2 \qquad 3$$

where j_i is the initial jet orifice height from the bed, and j_p is the potential core length (6.3x nozzle diameter). The bed shear stress for which no longer erosion takes place, is denoted the critical shear stress. Once this is determined, the rate of erosion is coupled to the excess shear stress ($\tau - \tau_c$) (See Equation 1a) to determine the soil erodibility. Different methods of interpretation of the data have been developed which differ in the datapoints that are included to define the soil erodibility. The values found for the critical shear stress and soil erodibility are also dependent on the range of stresses to which the clay was exposed. The results of the JET have shown that the erosive behaviour of clay under high stress conditions is different from the erosive behaviour of clay under low stress conditions. It is therefore important to apply a representative range of loads when performing the JET on levee soil. Also, the variability in erosion parameters appears to be a function on the degree of loading applied to the clay.

3.3.4 Rotating Cylinder Test (RCT)

The rotating cylinder apparatus was proposed by Moore and Masch (1962). It consists of an outer rotating cylinder rotating around a stationary inner cylinder. The inner cylinder consists of a soil wrapped around a centre rod. The gap between the two cylinders is filled with rotating fluid. The shear stress is measured on the centre rod via the applied torque. The drill hole apparatus was developed to improve over the rotating cylinder test. The amount of erosion could be determined from collecting the eroded samples, and weighing them after oven drying them. The advantages of this test is that shear stresses acting on the sample could be measured directly and that high shear stresses could be applied to the sample. The disadvantage is that the test cannot be performed in the field. Van Essen & de Groot (2003) noted that shear stresses obtained from the erosion apparatus match the shear stresses found in the water tongue, under the assumption of a fully developed boundary layer.

3.3.5 Pinhole and Hole Erosion Test (HET)

The hole erosion test evolved from the Pinhole Erosion Test (Briaud, 2019), which was designed to simulate the leakage effects in levees. During the pinhole erosion test pressurized distilled water is passed through a hole with an initial diameter of 1mm. The advantage of the pinhole erosion test is that it directly measures the dispersibility of clay soils.

The Hole Erosion Test is based on the Pinhole Erosion Test. During the Hole Erosion Test, soil is compacted in a standard compaction mould with a diameter of 100 mm. The test consists of forcing water through a pre-drilled hole with a diameter of 6 mm and recording the mass removal per unit area as a function of time. The water tank can maintain a variable head ranging from 50 to 800 mm corresponding with a flow velocity of approximately 1-4 m/s. As erosion progresses, the diameter of the hole increases and flow velocities decrease. The moment that erosion no longer takes place, the applied shear stresses match the critical shear stress. The soil erodibility parameter then follows from substituting the critical shear stress, the measured erosion rate, and the derived applied shear stresses in the erosion equation. The power coefficient is thereby often assumed to be unity.

3.3.6 Borehole Erosion Test

The Borehole Erosion test is a new in-situ soil-erosion test proposed to measure the erosion of the vertical walls of a borehole during wet rotary drilling. The result is a profile of soil erodibility as a function of depth. The test has been shown to work for clay and sand (Briaud, 2017). The principle of the Borehole Erosion Test is similar to that of the Hole Erosion Test with the advantage that the test can be performed in-situ and that values for the erosion resistance can be obtained over a large depth.

3.3.7 Impact pressure machine

The test methods above do not account for the impact of crack formation in clay on the erosion resistance. The impact pressure machine consists of a water filled vertical pipe. The vertical pipe can be positioned in a range from 50 to 165 cm above a soil sample. By releasing the water from the pipe on the soil sample, a wave impact is simulated. The maximum impacts correspond to wave heights of 1.2m. Husrin (2007) applied this test on clay samples with initially a water filled or air filled crack. The results of the tests served to analyse how a wave impact propagates in a crack, and how different soil parameters influence the erosion resistance of the clay.

Besides the JET and the Borehole erosion test, most tests are designed to be performed in a lab. The overview given above is meant to be illustrative and is by no means conclusive. Briaud (2019) gives a more extensive overview. Some important things to note are that each test is designed to represent the load during a different erosion failure mechanism. Where the JET simulates the impact of a cascading flow during headcut erosion, the HET simulates leakage erosion. Wahl et al. (2009) compared the predictions for the soil erodibility and critical shear stress that followed from the different tests. Paired specimens were created with identical compaction moisture content and compaction effort and tested by both the HET and JET methods. A total of 25 HET and 28 JET's were performed. On average the critical shear stress found with the HET was order of magnitudes higher than the critical shear stress found with the JET. Ellithy et al. (2018) performed tests with the JET and flume on the same soil samples. It was noted that the critical shear stress and erodibility coefficient measured by the JET were conservative compared to the flume results. This is likely due to the difference in hydrodynamics, and the amount of momentum and energy transferred with the bed during a parallel flow compared to a perpendicular flow direction. The flume tests also showed that a non-linear relation between the erosion rate and shear stress could be more representative. It should thereby be noted that the prediction for the soil erodibility and critical shear stress depend on the way in which data is interpreted. Differences in interpretation give rise to order of magnitude differences in soil erodibiliy and critical shear stress (Boucher et al. 2019). For the mixture containing no fines. The results of the JET tests tended to overestimate the degree of erodibility for all sand mixtures.

Several researchers attempted to relate the critical shear stress to the soil erodibility. However as can be seen from Figure 10, no correlation exists.

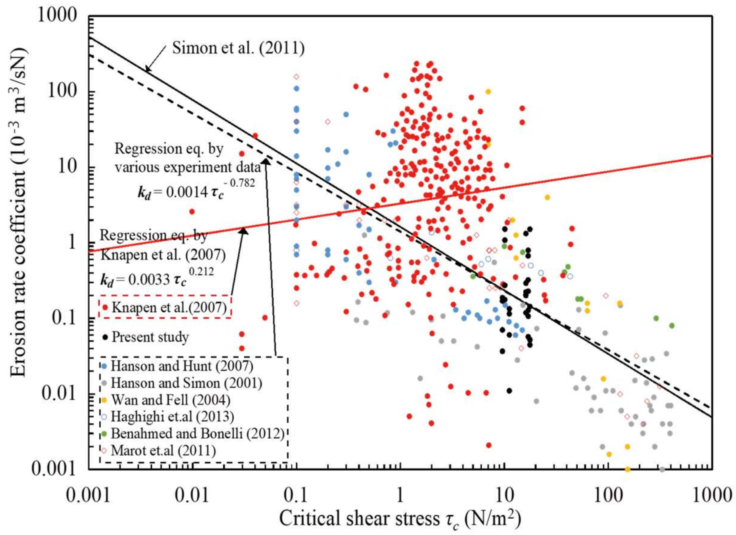

Figure 10. Relationship between τ_c and k_d in previous works and regression equations for k_d. (After, Yagisawa et al. 2019)

Husrin noted that the critical shear stress that followed from the Rotating Cylinder Test (RCT) (GeoDelft, 2003) was much smaller than the critical stress based on a single impact for the same remolded samples of Cäciliengroden and Elisabethgroden clay. Where the RCT gave a critical shear stress of 0,1kPa, the critical shear stress found with the impact pressure machine was 24,75 kPa. Van Essen & De Groot (2003) assumed that the shear stresses under a wave tongue under the assumption of a fully developed boundary layer match the shear stresses induced during an RCT test. It is questionable if the RCT could be used to resemble the erosion resistance by wave impact.

Each of the tests can be used to determine a soil erodibility parameter and critical shear stress. Problems arise when trying to calibrate all applied loads during HET, JET, RCT, and other tests to simply shear stress loads. Briaud suggests that the cause of these discrepancies is that soil erodibility depends on three types of stress: pure shear stress, turbulent fluctuations of shear stress, and turbulent fluctuations of normal stress. By relating the erosion rates to shear stresses alone, errors are introduced. For non-dispersive soils differences in findings for the soil erodibility increase to 2 orders of magnitude (Lim, 2006). Wahl et al (2009). Nevertheless, by comparing the outcomes of specific tests on different soils, the tests do give qualitative insights into how soil properties influence the erodibility. These qualitative insights have been outlined below.

3.4 How soil properties affect erosion

3.4.1 Clay

Lim (2006) compared the erosion process of partially saturated clays to the erosion process of fully saturated clays. Lim (2006) thereby compared the results of the RCT with the HET. Husrin (2007) performed experiments with the impact pressure machine to evaluate the presence of a water filled or air filled cracks in clay, on the erosion resistance. Husrin (2007) and Lim (2006) noted that the following soil parameters influence the erosion:

- Type of clay: Clay with a higher sand content was less erosion resistant and clays with a respectively high relative density were more erosion resistant (Van Essen & De Groot, 2003; Lim, 2006).

- Clay homogeneity: The homogeneity of clay plays an important role in the stress distribution. Inhomogeneous clay is subject to local weak spots through which it fails more rapid. It should be noted that Husin (2007) performed the experiments on prepared samples in which lumps of clay were prevented by pre-treatment.
- Water content: Wan & Fell (2002), Wan & Fell (2004), Wan & Fell (2004b), Wan (2006), Lim (2006), and Lim (2009) found that most clay soils tested are more resistant to erosion, and erode up to several orders of magnitude slower when saturated than in partially saturated form. They based this on tests with the HET and RCT. This did not apply it to silt, but only to clay. Husrin (2007) performed tests with the impact pressure machine on clays with various water contents. Clays tested at the recommended water content were a factor 10 more erosion resistant than clays with a high water content. On average, samples compacted at the recommended water content needed 10 times more hydraulic impacts with the impact pressure machine than samples compacted at the maximum water content, for the amount of erosion to be the same. For moderate clay, the maximum water content was 25.6%. Clay with a recommended water content (I_c>0.75) is more erosion resistant than clay with a high water content (0.5 <I_c<0.75). The water content in clay also determines the level of matric suction present. In the summer the suction can exceed 100m water column. The sensitivity of clay for the change in water content is indicated by the plasticity index.
- The plasticity index is related to the water content as it indicates the sensitivity of clay for a change in water content. Clays with a plasticity index <18% tend to erode faster than clays with a higher plasticity index.
- Compaction: Loosely packed clay is less erosion resistant than well compacted clay. Lim (2006) and Wahl (2008) noted that the soil structure strongly affects erosion properties. Erosion rates are significantly higher when the soil is compacted dry of the optimum moisture content and the soil forms aggregated particles and micro cracks. These allow for erosion by blocks instead of individual particles.
- Crack dimension: The formation of cracks depends largely on the water content during construction. No cracks were noted to form in clays with a water content during construction of 35%, whereas cracks did form when constructing from clays with a water content of 52%. The results found by Husrin (2007) were different from the results found by Rohloff and Stanczak (2006). The differences are expected to lie in the preparation of samples. In Rohloff and Stanczak (2006) hard lumps of clay were found in the samples due to no pre-treatment to avoid these. Also the water content in the clay samples was higher due to a lack in the degree of compaction. The dimensions of the crack also determine the magnitude of the propagated pressures in the crack.
- Dispersivity: Dispersive clays tend to go in suspension without a water flow required. The dispersivity of clay is influenced by the clay mineralogy. Clays with a high exchangeable sodium percentage tend to be more dispersive. Low pore water salt concentrations were found to lead to greater dispersivity. Consequently clays located in a more salty environment appear to be more erosion resistant. The clay fraction significantly influences the erosion behaviour of clay. Clays must remain electrically neutral. Clay molecules carry a negative charge which attract positive particles and ions in the soil pore water. When two clay particles come together, their similar charge will cause them to repulse. When the repulsive forces exceed the Van der Waals attractive forces, the soil disperses. A high concentration of salt in the water reduces the repulsive forces, benefitting the erosion resistance. The higher the salt concentration in the water, the more erosion resistant the soil is. The influence of dispersivity could play a role in the case of changing salt-fresh conditions.

- Temperature: An increase in water temperature or a decrease in soil temperature both give an increase in the susceptibility to erosion. However the impact is within one order of magnitude and therefore relatively small.
- Treatments: Geotechnical characteristics of soils are immediately affected by the addition of lime due to the influence of the Ca^{2+}ions coming from the lime. The lime induces a rearrangement of the contacts between the particles to compensate the electrostatic changes and leads to flocculation. This gives a reduction in the plasticity and compaction characteristics of the clay. The addition of lime leads to cementation of the clay. After 14 days the treatment by lime causes both the critical shear and the soil erodibility to decrease. However the reduction in soil erodibility outweighs the reduction in critical shear stress. Also Robbins et al. (2011) performed JET tests on soil samples to determine the effect of fly ash treated and lime treatments on the erodibility of the soil. The results showed that lime has the potential to improve the erosion resistance of the levee, however the treated sections showed little increase in erosion resistance compared to the original levee soil. This result opposes the results obtained by the Texas Transport Institute, who performed erosion laboratory tests on lime treated and fly-ash treated Bonnet Carre clay. These tests were performed with the Erosion Function Apparatus. The reason for the difference was believed to be the construction method. In the field, the fly ash was added several weeks before construction causing some hard lumps to form inside the soil prior to compaction. This caused for a heterogeneous mixture (Robbins et al., 2011). Robbins et al. (2011) also testes Lightweight treated soils (LTS). This is a cement stabilized clay created by combining soil slurry, cement and air foam. It has been developed as a fill alternative in Japan, Thailand, Korea, and China. Compared to lime treated soil, LTS is slightly weaker, more ductile and less erodible.
- Soil structure: The presence of a soil structure dominates the civil technical properties of the clay and negatively affects the soil erodibility. Structures form as a consequence of the shrinking and swelling of clay, by burrowing of animals and insects, and by the rooting of vegetation (TAW, 1996)

Briaud (2017) investigated whether it would be possible to find proper linear regression relations by plotting the erosion relation against different soil parameters like the plasticity index. All correlations were poor. This difficulty has also led to the use of erodibility classification charts to classify soils which are introduced in Chapter 4.

3.4.2 *Sand and gravel*

Corcoran et al. (2016) focused their erosion research on sand and gravel soils with a minimum of 95% compaction according to the standard proctor test and a close to optimum water (± 2%) content during compaction. Flume experiments were performed to evaluate the susceptibility to erosion of materials. For coarse-grained materials, the particles susceptibility to hydraulic loading was mainly affected by the size, shape, and density of the particles (Ellithy et al. 2020). Ellithy et al. (2020) performed flume tests on 6 mixtures of soil. Materials were compacted using the Standard Proctor test (ASTM D698-12). The optimum water content for compaction was between the 3 and 6 %. The power in the erosion relation during these measurements exceeded unity. The results from the JET and Flume test resulted in insights into how material properties affect the erodibility of sand.

- Porosity and dilation: Hanson (2007) and Morris (2008) concluded that the erodibility of material is dependent on the compaction moisture content and compaction energy. Under low velocities, particles become entrained by the flow when the lift force, drag force, and shear force acting on the particles exceed the stabilizing forces. When the hydrodynamic forces acting on the soil increase, the erosive behaviour of soil changes. Instead of individual particles being picked up by the flow, during erosion layers of particles are sheared off the bed (Van Rhee, 2010). During soil detachment, particles and water exchange at the bed. During this exchange, momentum is transferred. Above the depth at which the shear stresses equal the shear strength, the bed begins to move (Iverson, 1997; Iverson, 2000; Takahashi, 2009; Takahashi, 1981). For layers to shear, soil needs to dilate. The associated increase in pore volume needs to be accommodated by the pore water which requires a flow of water into the bed. This flow requires a pressure gradient over the bed which benefits the shear resistance. The larger the degree of compaction, the higher the dilation induced stabilizing effect is (Van Rhee, 2010; Van Damme, 2019). The material texture thereby also influences the increase in porosity required to allow for shear failure of particles to occur. The effects of dilation correspond well with observations that soil erodibility depends on material texture, compaction moisture content, and compaction energy (Hanson and Hunt, 2007; Morris et al., 2008).

- Permeability: According to the Shields theory, fine particles are more susceptible to erosion than course particles. However, in the case of high shear stresses this no longer applies. When flow velocities exceed approximately 1 m/s the lower permeability of soils with fines gives a lower rate of erosion than in the case of soil consisting of course particles. Ellithy et al. (2020) noted that by adding a 1-5% fines to sand, reduces the erodibility by as much as 40%. Visser (2018) was involved in a research project whereby bentonite was added to sand. This significantly reduced the erodibility of the material. The lower the permeability is, the higher the stabilizing effect of the dilation effect will be. For a bed shear stress varying between 2.4 and 50.3 N/m^2, it was noted that mixes with a smaller <2mm D_{50} tended to erode faster than mixes with a D_{50} >20mm despite the same fines and clay content in the mixtures.

4. Categorization

The aim of the POV DGG is to facilitate the design of levees using locally sourced soil material. In line with the story of the levee concept, this requires that erosion characteristics of soil are accounted for in levee design. The development of breach models, and erosion apparatuses have predominantly focused on erosion of clay and sand. The question is how best to account for the erosion properties of local soils considering inconsistent predictions of soil erodibility following from the wide variety in erosion tests (Section 3.3) , and the unknown influence of soil parameters (Section 3.4).

In anticipation to the large problems with the uncertainty surrounding the identification of soil erodibility, it is preferred that the interpreted outcomes of erosion tests are calibrated against the erosion relations based on large-scale experiments by repeating the erosion tests on the same soil. Using the calibration relation, erosion test apparatuses could be applied to various soils to extend the range of applicability of erosion relations based on large-scale experiments. By describing the methodology to follow when designing levees with the use of local soil, the choice for any specific erosion test, or interpretation method is left open provided that each test is inter-calibrated against large scale-tests or other calibrated small scale test. Chapter 5 expands on this in more detail and discusses what steps may be needed to achieve this.

This chapter discusses the categorization, which can be used to facilitate designing levees with local soil. For both the erosion and the breach modelling the current level of knowledge and the objectives for the future have been given in a tabular format at the end of each of the subsections.

4.1 Categorization of erosion

As discussed in Chapter 3, one of the major problems with analysing available erosion data is that soil erodibility and critical shear stress parameters derived from different tests are not in agreement with each other, and depend on the method of interpretation (Boucher et al. 2019). Despite qualitative descriptions available of how soil properties of clay and sand influence the soil erodibility, little consensus has been achieved on how to quantify this influence. Finally, in some cases the qualitative descriptions of the influence of soil parameters seem to conflict, like for instance in the case of the water content of clay.

In order to deal with conflicting results the graphical representation method, outlined below, was introduced by Greg Hanson (See Figure 11) (Briaud, 2019). In line with this representation method, Briaud (2019) developed the NCHRP erosion spreadsheet which already contains 975 results from respectively the HET, JET, EFA, RCT, and flume tests. This database contains information on:

- The critical velocity
- The critical shear stress
- The erodibility related to velocity
- The soil erodility related to the bed shear stress.
- Erosion Category

The graphical representation (See Figure 11) gives a rapid overview of the erosion characteristics of soils. An added advantage is that the method could be used to obtain first order estimates of the erodibility of soil types, which could be used in preliminary designs of levees. It should be noted that this first indication is dependent on the testing method and interpretation method used and therefore should be created per type of loading. The method could also easily be extended to other soil types.

The critical values for the bed shear stress and velocity are determined by setting out the bed shear stress τ, or flow velocity v against the erosion rate E (See Figure 11). It is interesting to note here that according to the categorization by Hanson, fine sand is believed to erode faster than course sand. This conflicts with the theory of Van Damme (2020) and the experimental outcomes of Bisschop (2018) who noted that, due to the influence of dilation, fine sands erodes slower under high shear stresses than course sand. The critical bed shear stress, or critical velocity is found by determining the imaginary intersection with respectively the x axis which is often given by the bed shear stress τ or flow velocity v. Since it is impossible that both τ and E, and v and E describe a linear relation, the soil erodibility is purely based on the initial points on the curve and not the full curve.

A disadvantage of the log-log graph (see Figure 11) is that the linear lines do not correspond with a linear relation represented by Equation 1a. Consequently, the relations described by the lines are not linear. The critical shear stress found via extrapolation is likely not the critical shear stress that is found in the case of a linear plot. Another disadvantage of the applied categorization method is that for each soil a different curve can be created per testing method. In addition, it should be noted that, with exception of the hydraulic/wave impact tests (which have not been incorporated in the NCHRP erosion spreadsheet), all loads are translated into shear stresses. Even in the case of the JET, whereby the load is applied perpendicular to the bed, the rate of erosion is related to the shear stress. In the case of the JET, the flow is curved, while in the case of the HET, or EFA, the flow is parallel past the soil. Yet no account is made on how this may affect the derived critical shear stress, and consequently the soil erodibility parameter.

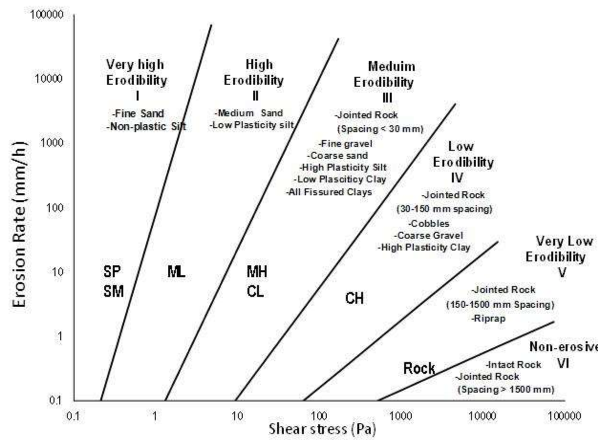

Figure 11: Soil erodibility chart, After Briaud (2019)

Finally, discrepancies arise from the method of choice for determining the soil erodibility from the test results. For the JET tests several methods are available to estimate soil erodibility. Each of these deduction methods gives a different prediction. Examples are the Blaisdell method, and the scour depth method. Bouchet et al. (2019) used a direct inversion of the scour depth method in combination with Monte Carlo Sampling techniques to derive the soil erodibility. This however led to estimates of the soil erodibility that were outside the range indicated in Figure 10. Efforts have been made to investigate this discrepancy (Boucher et al. ,2019).

The current categorization of soil gives the problem that much room is left open for interpretation of results. It is recommended that this is prevented, for example, by cross validation against a soil whose erosion characteristics has been determined by means of large scale tests. The international and national objectives are thereby in alignment. A similar graph as Figure 11 could be used to represent the relative increases in soil erodibility against calibrated soils for which large-scale tests exist. This has also been outlined in the overview of Table. 4.1. Recommendations are made in Chapter 5 on how to reach the specified national objectives.

Table 4.1: Summary of the (inter)national available knowledge on erosion.

	Current knowledge	**Objective for the future**
International	• Various small-scale erosion tests, and various interpretation methods to evaluate the erosion resistant properties of soil. • Graphical representation method to illustrate the relative erosion sensitivity	• Develop means to provide high quality estimates of soil erodibility for application in breach models for various types of erosion mechanisms.
National	• Insights into the erosion process by wave impact based on large-scale wave impact tests. • Ability to perform large-scale wave overtopping, wave run-up, wave impact, and overflow tests	• Inter-calibrate small scale tests against large scale erosion test outcomes • Graph the relative increases found in soil erodibility after calibration against the outcome of large-scale tests.

4.2 Incorporating erosion in breach models

Breach models have been developed to simulate both the breach formation and growth processes in the case of overflow and piping for homogeneous clayey and sandy levees. For the case of erosion due to wave impact, a levee erosion model has been developed in the Netherlands (Klein Breteler, 2019) to simulate the process up to breach formation for a levee with a clay cover layer and sand core. No commercially available breach models are yet available to simulate the process of breach formation due to wave overtopping and wave run-up. In line with the objectives of the POV DGG it is preferred that the range of applicability of the erosion relations applied in the breach models is extended beyond the current soil types (Mourik, 2017). The extension of existing methods to include failure by wave run-up or overtopping would benefit the design of levees. The applied erosion formulae should thereby be applicable to a wide range of soil types.

The current available breach models contain assumptions with regard to the generic process of erosion that are based on one specific failure pathway. This approach is in line with the international objective to use the models to predict the breach hydrograph. It should be noted that this objective differs from the national objective to evaluate failure pathways. The dominant failure pathway, often simulated, may thereby differ from the critical failure pathway, which gives the highest probability of failure. Provided that sufficient awareness is created around the assumptions underlying breach models, and that sufficient care is used in applying them, currently available modelling methods could serve probabilistic analyses and provide valuable insights in the processes of erosion.

Table 4.2: Summary of the (inter)national available knowledge on breach modelling.

	Current knowledge	**Objective for the future**
International	• Rapid breach modelling methodologies for homogeneous levees based on an overflow induced headcut or surface erosion failure mechanism, or piping	• Accurate breach formation and growth prediction models for estimating the breach hydrographs for use in flood risk assessments
National	• Rapid breach modelling methodology for wave impact	• Rapid simulation of levee erosion processes for the loading mechanisms: wave impact, run-up, wave overtopping, and overflow, irrespective of the initial levee geometry. The aim here is to account for the residual strength • Be able to apply the models within the story or the levee concept such that multiple failure pathways could be investigated.

5. Discussion

On the basis of the information provided in the previous chapters, this chapter sets out what steps are required to eventually incorporate the application of local soil in an evaluation and design instrument for levees that fits within the Dutch probabilistic approach to design levees that comply with the legal norms. The lessons developed should be adopted in technical guidelines. It is thereby recommended to illustrate the methodology by means of examples.

5.1 Applying the erosion formulae in levee safety analyses

In order to evaluate the safety of levees, erosion characteristics of soil need to be entered in levee erosion models or breach models, which facilitate probabilistic calculations, and can be applied within the story of the levee concept. For wave impact and overflow/wave overtopping some possible approaches are outlined below.

5.1.1 Modelling breach formation by wave impact

Van Boven (2018) and Klein Breteler (2019) have applied breach models in the probabilistic assessment of levees exposed to wave impact (Mourik, 2017) whereby the breach was initiated by waves impacting on the waterside slope of a levee. The applied breach model was developed and calibrated against metre-scale tests in the Delta Flume. In the breach model, the volume of eroded soil is related to peak stresses via a soil erodibility parameter. By extending the range of applicability of the soil erodibility parameter to other soil types, the probabilistic safety assessment could be applied to levees constructed of locally available soil, or treated soils.

5.1.2 Modelling breach formation by wave overtopping/overflow

Hanson et al. (2005) developed a modelling approach to determine breach formation in the case of headcut erosion by *overflow*. This modelling method has been validated against large-scale tests, and has been adopted in several process-based breach models (Davison et al. 2013; Van Damme, 2012). Other breach models developed for headcut erosion thereby assume a similar development process of the breach (Zhu et al., 2008). For the case of *wave overtopping* no breach model has yet been developed. However, similar processes of breach formation have been witnessed for wave overtopping during large-scale experiments performed on a redundant levee bordering the Wijmeers polder in Belgium (Lindenbergh & Herrero-Huerta, 2017; Ponsioen & Van Damme, 2016). The breach formation is therefore likely to follow a similar process of headcut erosion during wave overtopping as during overflow, despite a large expected difference in the rate of erosion. The general description for breach formation of Hanson et al. (2005) could therefore likely be applicable to wave overtopping as well. Nevertheless, before applying the model description to overtopping it is recommended to first develop relations for a) the load that is experienced by the levee during the different stages of breach formation, and b) the rate of erosion that occurs due to the load.

In case levees consist out of sand, with or without a clay layer present on the waterside slope, the dominant erosion process is uncertain, yet often assumed to be surface erosion. Two large-scale tests, similar to each other, have been performed on a medium sand levee (Visser, 1996) which support the assumption of surface erosion. Pure sandy levees are rare as often some erosion resistant, impermeable layer is present. Insufficient knowledge is yet available on the dominant erosion process when the waterside slope contains an impermeable layer or other variations in design. The process of erosion by wave overtopping is also unknown for sandy levees, which hampers levee managers in fully accounting for the residual strength of levees

5.1.3 Failure criterion.

Currently, breach models determine the extent of erosion, but do not comment on when the levee is assumed to have failed. Steep slopes that arise during erosion by overflow, wave overtopping, or wave impact could trigger a geotechnical failure due to lack of stability. This relation between failure mechanisms has currently not been adopted in any breach modelling approach, as it has not yet been observed during previous experiments. However, the number of large-scale experiments is small compared to the number of variables that could determine whether a geotechnical failure could be initiated. It is therefore regarded insufficient to state that this will never occur and a check for the geotechnical stability of the levee during breach formation needs to be included if significant within the range of validity of the model. To allocate a probability of failure to a levee, a failure criterion needs to be set. Criteria for levee failure could be:

1. soil has been removed over the full width of the crest of the levee by a single, or by a combination of failure mechanisms (Van Boven, 2018; Klein Breteler, 2019). When erosion continues after this point, then Stages 3 and 4 in the breach formation initiates. During these stages the breach discharge rapidly increases over a small amount of time (See Figure 1)
2. The erosion of the levee has extended beyond the point for which the breach models were validated based on large-scale tests. In most cases this is limited to the failure of the cover layer. In the case of limited experimental data available on the full process of breach formation also expert judgement could be applied to extent the range of applicability.

5.2 Extending the use of erosion formulae to local soil

Currently available breach models (Mourik, 2017; Hanson et al., 2005; Van Damme, 2012) contain empirical erosion relations that have been developed and validated for a range of conditions. The range of applicability of erosion relations, included in breach models, can be extended to broaden the range of applicability of breach models. Global erosion processes must however remain in line with, for example the headcut formation process. The linearity of the erosion relationship may also not change.

To extend the range of applicability of erosion relations, centimetre-scale erosion tests (see Section 3.2), need to be inter-calibrated against a known standard based on meter-scale erosion tests. This is discussed in Section 5.2.1. Section 5.2.2 discusses how to deal with the uncertainties of the models. When performing erosion experiments it is recommended to distinguish between the soil erodibility of the grass cover and turf layer with respect to the soil layers beneath, since the grass cover strongly influences the erosive properties of soil. This would also allow designers to account for the higher erosion resistance of grass covers in levee designs.

5.2.1 Correlating outcomes erosion tests

Erosion relations for wave run-up, top part of the wave impact zone (Klein Breteler, 2020), and wave overtopping are currently planned to be developed based on Delta flume experiments (Klein Breteler, 2020) and large-scale experiments at the Hedwige Prosperpolder (Van Damme et al., 2017). Erosion relations for wave impact have been developed by metre-scale tests on soil samples from levees of the Oosterland, Ferwert, Wieringermeer, Kruinigen and Perkpolder.

Before allowing for the use of small-scale erosion tests to extend the range of validity of existing erosion relations it is essential to gain confidence that results from erosion experiments at centimetre-scale can be used to simulate the processes of erosion at metre-scale. It is therefore recommended to inter-calibrate cm-scale erosion tests against metre-scale erosion tests.

Although no consensus yet exists on how to inter-calibrate centimetre-scale field or lab erosion tests, like the HET, JET, or EFA, to metre-scale tests that represent actual hydraulic loads on levees, four recommendations can be made:

1) For a proper interpretation of results, small-scale erosion tests should aim to represent the actual hydraulic loads on a levee as accurate as possible. The Impact pressure machine, could for example be used to simulate erosion by wave impact, and the JET to simulate the effects during headcut erosion.
2) The presence of cracks may determine the erosion resistance of the clay layer as a whole. It is therefore recommended to develop tests which can account for the presence of these cracks.
3) The range of loads applied by the small tests should approximately match the range of hydraulic loads. The maximum load applied by the small-scale tests should therefore match the load applied during large waves, of high overflow discharges, whereas the minimum load should be equal to the loads exerted by for example small waves, or smaller.
4) The inter-calibration should be performed based on a sufficient number of test results with the small-scale tests to get statistical convergence.

5.2.2 Dealing with uncertainties.

Inaccuracies in the existing erosion relations for clay are likely due to a variation in compaction moisture content, salt content, soil structure, and presence of cracks and other parameters (see Section 3.4). The erosive properties of soil are time-dependent in case cracks form, salinity levels change, or soil becomes more structured. It is essential that also these time effects are either accounted for, or monitored when designing a levee with a long life span. Past efforts, which aimed at relating the change in soil erodibility to changes in soil parameters, have been futile for clay. The soil erodibility of clay is therefore a stochastic variable. As an indication, the coefficients of variation for soil erodibility in the Delta flume were approximately 25% for clay and 27% for boulder clay.

Previous tests performed with small-scale test apparatuses on the same dike material indicate a range of uncertainty of orders of magnitude around the soil erodibility parameter and critical shear stress. This is likely due to the higher variability in erosion resistance on small scale. Accounting for the full range of uncertainty following from centimetre-scale erosion tests leads to overly conservative designs. It is therefore recommended to develop methods to determine the range of uncertainty to account for in levee designs by:

a) calibrating the outcomes of a statistical significant number of small-scale tests performed on an area of several square meters against the outcome of a large scale test, on the same type of soil.
b) applying the experience obtained with statistical averaging the results from geotechnical lab results.

Once determined, differences in measured soil erodibility on several locations along a dike stretch serve as an indicator of the length effect for soil erosion. In levee design analyses, this length effect for erosion currently has been set to 1 (Van Boven, 2018; Klein Breteler, 2019). However, it is questionable whether this factor 1 is also representative for dike erosion due to unknown variations in erosion resistance of the subsoil along a levee section. Spatial correlations in soil erodibility are certainly not perfect and identifying the critical cross section is challenging. The system failure probability will therefore be higher than the cross-sectional failure probability.

6. Recommendations

Based on the analysis outlined in this report the following recommendations are made to the POV DGG:

1. Extend the range of applicability of breach formation models by extending the range of validity of the erosion relations in the breach models.
2. Develop a recipe for how to inter-calibrate the outcomes of cm-scale erosion tests to an established standard based on metre-scale erosion tests in order to extend the range of validity of erosion relations in numerical models. This recipe should:
    a. include a description of how to inter-calibrate the outcome of small-scale tests to large-scale tests whereby the calibration is based on multiple measurements with the small-scale test,
    b. include a description of how to derive the range of uncertainty in soil erodibility and critical shear stress based on an statistically significant number of tests using the inter-calibration procedure, and statistical averaging methods,
    c. prescribe for one example test series how to perform the inter-calibration, and thereby highlight the need to repeat this process per method of interpretation of the test results,
    d. explain how to account for the uncertainties due to the temporal changes in soil erodibility and critical shear stress,
    e. explain how to apply a length effect to erosion parameters. This is needed to translate the failure probability for a levee cross section to that of a levee stretch,
    f. be illustrated by means of examples of successful applications.

   Once completed the recipe should be included in technical guidelines.
3. Besides these technical recommendations it is recommended to regularly align the activities performed by the POV DGG on erosion with the short term, medium term, and long term research activities executed as part of the KvK ("Kennis voor Keringen") programme such that the initiatives enhance each other.

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