Deltares

Dike erosion landside slope

Progress report 2023 Sito-PS KvK DE1

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Summary

The final aim of the research described in this report is to:

> *"Develop a relation for the erosion of the landside slope by wave overtopping for various types of soil in a form that can be incorporated in the Dutch instruments applied for the safety assessment and design of the primary flood defences (known by the Dutch acronym "BOI)".*

This report is intended as an intermediate report and only holds intermediate conclusions concerning the performance of a clay erosion model in combination with small scale laboratory tests to obtain the erosion parameters.

In collaboration with international partners, a computational model, OTE2C$_{ISL}$ has been developed that should be able to:

- Describe the erosion of a grass cover in accordance with the Dutch Cumulative Overload Method.
- Describe the erosion of the remaining clay cover underneath the grass cover.

The focus has been on the second part. For this part, a widely used relation is used relating the erosion rate to the product of a so-called erodibility coefficient, E_d, and the exerted shear stress above a threshold called the critical shear stress, τ_c.

Empirical data in this field is scarce. Use has been made of the two wave overtopping tests on bare clay on the landside slope of the dike at the Hedwigepolder where irregular waves were applied. For this location, erosion parameters from Erosion Function Apparatus (EFA) and Jet Erosion Test (JET) tests are available too. Other data available are one wave overtopping test on bare clay at Delfzijl carried out in March 2007, where samples have been taken for EFA tests in June 2023 as part of the current project. More recently, near the end of 2023, additional wave overtopping tests have been carried out near Lelystad. Samples for EFA tests have been taken on the deeper boulder clay, for which limited data on the erosion are available, while more detailed erosion data is available from tests on the upper 'well compacted' clay. The Lelystad data still needs to be analysed.

The combination of model and laboratory tests for parameters was validated with large scale wave overtopping tests at two locations. From this validation it can be concluded that the combination of model and laboratory tests is by far insufficient for prediction purposes in BOI.

The laboratory tests for the Hedwigepolder generally lead to a significant overestimation of the erosion rate parameter values to postdict the observed erosion. For the Delfzijl case, the laboratory tests, the opposite is true. However, it is noted that the samples were taken 16 years after the overtopping tests and in relatively dry conditions with a low moisture content. Currently there is no conclusion possible what the cause is of the large differences. This could either be the model itself or the loading part of the model or the difference between lab parameters and bulk parameters needed in the model. Or a combination of these factors.

Contents

1 Introduction

1.1 Aim of the research

The final aim of the research described in this intermediate report is to:

> *“Develop a relation for the erosion of the landside slope by wave overtopping for various types of soil in a form that can be incorporated in the Dutch instruments applied for the safety assessment and design of the primary flood defences (known by the Dutch acronym “BOI)”.*

Overflow is yet not included because of the focus on an empirical basis for the validation that consists of wave overtopping conditions only.

1.2 Description of the research and planned result

This project is the continuation of the ‘Theme Erosion’ of the Interreg 2Seas Polder2C’s project. Together with ISL, ESTP and Cerema from France and UC Louvain from Belgium, the work is continued on a model by which the amount of erosion on the landside slope of a dike, caused by wave overtopping, can be predicted.

The model was calibrated by the measurements from wave overtopping tests on a dike slope along the Hedwigepolder in February 2022, of which the upper 20 cm, including the grass, yet not all the grass roots, had been removed. The model is validated by results from similar tests at Delfzijl from 2007. In 2024, this may be supplemented by results from tests near Lelystad in 2023.

The model is implemented in a Python code by which the erosion of the clay layer on a landside slope, resulting from a series of overtopping waves, can be calculated. The Python code is a prototype; therefore, it cannot be implemented into BOI right away. It is the intention to couple the code to the Dutch HydraRing software in the future, to enable probabilistic calculations for Dutch primary dikes to estimate the influence of including clay erosion on the landside slope on the probability of flooding.

The Python code is presented in Annex C.

Besides the clay erosion model and software development, project coordination tasks were performed as a part of this research.

Apart from Rijkswaterstaat-WVL, the following parties are involved:
- Deltares (safeguarding practical applicability, especially for the Dutch context, and validation of the model with the Delfzijl measurements).
- ISL (a French engineering company | programming the model).
- ESTP (a Paris university | lab tests of erodibility of clay and the interpretation thereof).
- Cerema (a French governmental institute | applicability to the French context).
- UC Louvain (a Belgian University | providing detailed measurement data of the tests at the Hedwigepolder).

1.3 Planned activities and guideline through this report

The following activities were to be conducted:
1. Coordination of activities between the various partners in the project *(§2.2).*
2. Contributing to discussions to achieve such a quality of (intermediate versions of) the ISL model that this becomes suitable for the probabilistic safety assessment of dikes *(§2.3).*
3. Assisting in sampling at Delfzijl near the location where in 2007 wave overtopping tests were conducted, to enable ESTP to conduct EFA tests – provided ESTP is willing to conduct these tests and the sampling succeeds *(§2.4).*
4. Validation of the ISL model using data of the Delfzijl tests *(§3.3).*

5. Estimating the uncertainties in the ISL model and the parameters of it, based on the large-scale tests and the results from supporting small scale tests, and a sensitivity analysis to give recommendations for further research *(§3.5).*
6. Illustration of the influence of including the resistance to erosion of the clay cover (underneath the grass) on the probability of failure for a case that is yet to be defined *(§3.6).*
7. Stay involved with the sequel to Polder2C's, currently under the name of Bonsai. The aim of Bonsai is to prepare for the impact of 50 and 100 years of climate change in North-West Europe, particularly the influence on the condition of the clay covers of dikes and the erodibility thereof. Depending of the precise type of European funding and the associated conditions, Deltares will either participate as a partner or, like in Polder2C's, as a subcontractor. This participation (in relation to this research plan) will only take place under the condition that some of the contents of the Bonsai proposal will contribute to the improvement of the safety assessment of flood defences (and it also contributes to the aims of KvK) *(mentioned because of its relevance, but without budget claim and without further description in this report).*
8. Brief report of all activities, including processing comments on the draft version once *(this report)*.

Not mentioned above:

- Section 2.4 also describes the site near Lelystad where similar wave overtopping tests were carried out.
- Section 3.2 gives a description of the test conditions at the Hedwigepolder and the data from those tests, used for the calibration and validation of the ISL model.
- Section 3.7 gives some remarks on the modelling of erosion.
- Chapter 4 summarizes the results and conclusions.

2 Preparation and supporting activities

2.1 Introduction

The core of this report is the application of the ISL model to various situations, described in the next chapter. This chapter describes all preparation and supporting activities:

- The coordination of activities within the “Theme erosion” group (§2.2).
- The erosion model as provided by ISL (§2.3).
- The main characteristics of the sites at Delfzijl and also Lelystad, where samples were taken (§2.4). The Lelystad site was added early October 2023.

2.2 Coordination of the activities within the “Theme erosion” group

The “Theme erosion” group consists of members of the partners already mentioned in §1.2. This group was established during the Polder2C’s project. After a long end-of-the-year break, the group reconvened on April 19th, 2023 in an online meeting.

The collaboration workplan discussed on April 19th is given in Annex A. The minutes of all meetings of the group as a whole are given in Annex B.

Apart from these group meetings, various meetings of sub-groups and bilateral meetings were held.

2.3 Erosion model ISL – “OTE2C$_{\text{ISL}}$”

ISL has modified the AREBA code to arrive at a model for erosion of a landside slope due to overtopping erosion. Details are given by Jellouli et al. (2023), some assumptions and formulae are reproduced in this section for clarity.

The code is only valid for situations where the mean sea level is lower than the crest level. Both regular waves and irregular waves can be included. The code is given in Annex C.

2.3.1 Computing overtopping flow

The overtopping flow is calculated using the equations from the EurOtop Manual for gentle slopes and a positive freeboard. The code allows for the input of tidal characteristics with storm conditions super positioned on the astronomical tide, so unlike some other codes, like HydraRing[1], the water level during a simulated storm is not continuously at peak level by default. An example of the input is given in §3.2.3.

2.3.2 Overflow discharge of a single wave over time

Figure 2.1 shows in yellow the real discharge over time for a single overtopping wave. This is compared to the mean flow (assuming a wave period of 10 seconds), a rectangular approximation and a triangular approximation, all with the same average flow.

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[1] Yet, although HydraRing gives the peak values, in the calculation of the grass cover called by HydraRing the effects of the tide are properly included.

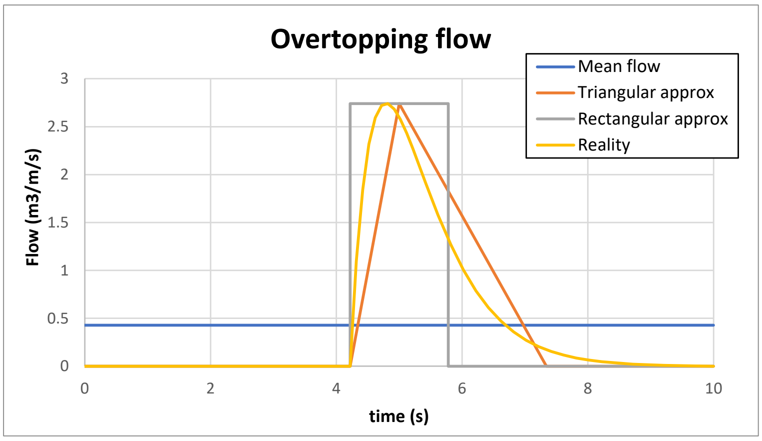

Figure 2.1 *Overtopping discharge over time for one single wave (example with $R/H_{m0} = 1$) (Jellouli et al., 2023).*

To accelerate the calculation process, initially the rectangular approximation is used. It is often assumed that erosion only takes place above a certain threshold, e.g. a critical velocity or a critical shear stress. If this threshold is exceeded, the erosion is calculated with the triangular approximation by applying a correction factor (see the part `def coef_corr` in §C.7). The influence is illustrated by Figure 2.2.

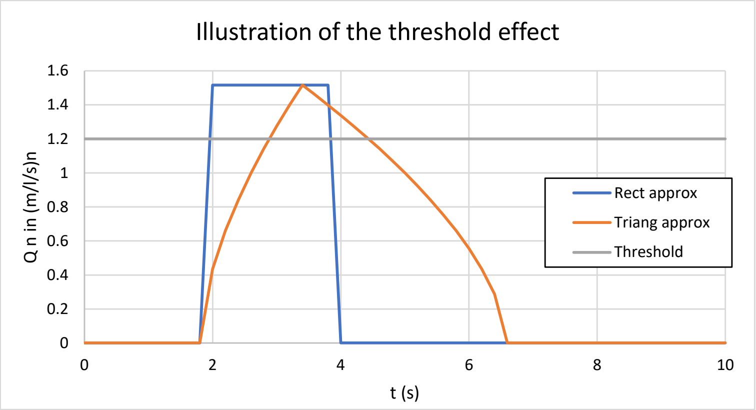

Figure 2.2 *Difference in eroding volume between the rectangular and the triangular approach above a certain threshold (Jellouli et al., 2023).*

2.3.3 Landside slope erosion from wave overtopping

Depending on the situation, erosion of the landside slope from wave overtopping may consist of several stages:

- Initiation of erosion on a slope covered by grass from grass erosion.
- Headcut formation on the landside slope.
- Headcut advance through the embankment crest.

In practice, these three stages may be followed by breaching through deepening of the headcut through the waterside slope (stage 4) and widening to both sides of the headcut (stage 5). In the OTE2C$_{ISL}$ code, only the first three stages are included.

For the initiation of erosion, the Cumulative Overload Method (COM) has been implemented as the only option. As this report focuses on situations where the (top part of the) grass sod has been removed already, this part is not detailed here. In the calculation grass can be ignored by setting the grass quality to zero.

For the second (and third stage), the erosion rate E_r [m/s] resulting in deepening of the headcut is computed, in case the contribution is positive, by:

$$E_r = K_d(\tau - \tau_c) \tag{2.1}$$

Where:

- K_d [m^3/Ns] is the erodibility coefficient that quantifies the erosion kinetics.
- τ [N/m^2] is the shear stress exerted on the soil.
- τ_c [N/m^2] is the critical shear stress, representing the threshold beyond which erosion is initiated.

During the second stage, the headcut formation, the shear stress on the erodible surface is calculated from:

$$\tau_1 = \rho g d_n S \tag{2.2}$$

Where:

- ρ [kg/m^3] is the density.
- g [m/s^2] is the gravity acceleration.
- d_n [m] is the normal depth (coded as `de`), calculated with the Manning-Strickler formula on the landside slope considering peak discharge.
- S [-] is the landside slope.

It is assumed that the erosion hole develops into a headcut. The flow then tends to plunge into the headcut, influencing the rate of downward erosion at the base of the headcut, the rate of headcut advance along the slope, or both. The shear stress is then calculated from:

$$\tau_2 = \ a\rho g h_c \left(\frac{E_d}{h_c}\right)^{0{,}582} \tag{2.3}$$

Where:

- α [-] is a coefficient used in the literature for the effective stress due to plugging flow, generally equal to 0.011 (and hard coded at present in OTE2C$_{\mathrm{ISL}}$).
- h_c [m] is the critical depth of the flow (coded as `dc` and calculated from the peak discharge q_{max} by $(q_{max}{}^2/g)^{1/3}$).
- E_d [m] is the erosion depth, in the code incrementally calculated from E_r multiplied by the time step, the ratio of time a wave is passing according to the rectangular approach and the correction factor tor a triangular approach as detailed in §2.3.2 (note: this is a more precise formulation than presented by Jellouli et al. (2023), where no distinction is made between E_r and E_d, although these parameters have different units).

The increase in erosion depth ΔE_d is calculated from the erosion rate E_r according to (2.1), considering the maximum of (2.2) and (2.3) provided this is larger than zero, multiplied by the timestep, the characteristic wave overtopping time[2] and the correction factor for the triangular approximation as mentioned in §2.3.2.

Regarding a, Jellouli et al. (2023) remark this coefficient needs to be calibrated by experiments. However, K_d and τ_c are basically also parameters that need to be calibrated from the experiments described in this report.

The advance rate of the headcut, upwards along the landside slope and seaward along the crest, is given by:

$$\frac{dx}{dt} = -C(qE_d)^{\frac{1}{3}}$$

Where:

- x [m] is the coordinate along the surface.
- t [s] is the time.
- C [s$^{-2/3}$] is the headcut parameter, now a value is calculated from K_d based on an approximation applied in HR Breach (see §C.3 under `Determine KD`).
- q [m^2/s] is the peak discharge per unit of dike length.

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[2] The characteristic wave overtopping time is a non-dimensional parameter indicating the overflow intensity over time. Its value is 0.25 for a regular sinusoidal wave in case of no freeboard and decreases with an increase of the freeboard.

- E_d [m] is the depth of the headcut.

Underneath the slope, erosion is limited to the base level of the embankment. Erosion of the crest is only allowed from the retreat of the headcut. In the Python code failure is considered to occur if the crest is eroded completely before the total storm period has passed. For future implementation and use in dike design and safety assessment the failure definition will have to be considered in more detail.

2.3.4 Handling load conditions

The erosion module is approached after preprocessing the input, which allows for a diurnal tide (see §C.8). In case of irregular waves, the wave heights are approximated in five steps (see §C.3, under ‘`RUN OTE2C`’).

Besides, a probabilistic module has been developed (see §C.9). Currently, five parameters can be considered as stochastic parameters:
- High tide levels.
- Significant wave heights
- Critical velocity (for grass erosion).
- Critical shear stress.
- Erodibility.

For these parameters, the cumulative distribution function should be provided to $\text{OTE2C}_{\text{ISL}}$ as a tabulated, piecewise approximation in separate CSV-files. The high tide levels and significant wave heights should be expressed in terms of daily distributions. The probability of failure presented as output refers to the probability of failure per year. When comparing outputs of $\text{OTE2C}_{\text{ISL}}$ and e.g. HydraRing, due care should be taken to ensure that indeed the same information is compared.

2.4 The test sites near Delfzijl and Lelystad

The tests at the Hedwigepolder were not unique, yet rare. Similar tests, on a dike slope from which the grass cover and some of the clay cover had been removed prior to the simulation of wave overtopping, have been carried out near Delfzijl and Lelystad, both in The Netherlands.

2.4.1 Delfzijl

In March 2007, three series of wave overtopping simulations were carried out on the landside slope of the sea dike east of Delfzijl as part of the Interreg ComCoast project. The location is indicated in Figure 2.3. The test arrangement is shown in Figure 2.4. The third test, on bare clay, had been assigned by the Dutch SBW program of Rijkswaterstaat. “Therefore the grass sod (upper 20 cm) was fully removed. The aim of the test was to obtain a better insight in the behaviour of the total system of grass sod + clay under layer and the clay layer only. Under SBW, prediction models have been developed for the behaviour of the inner slope by wave overtopping. The results of the tests can be used to validate or modify these prediction models (outside of the [s]cope of the present study).” (Akkerman et al., 2007).

Figure 2.3 *Location of the wave overtopping experiments near Delfzijl, indicated by the magenta square (Akkerman et al., 2007).*

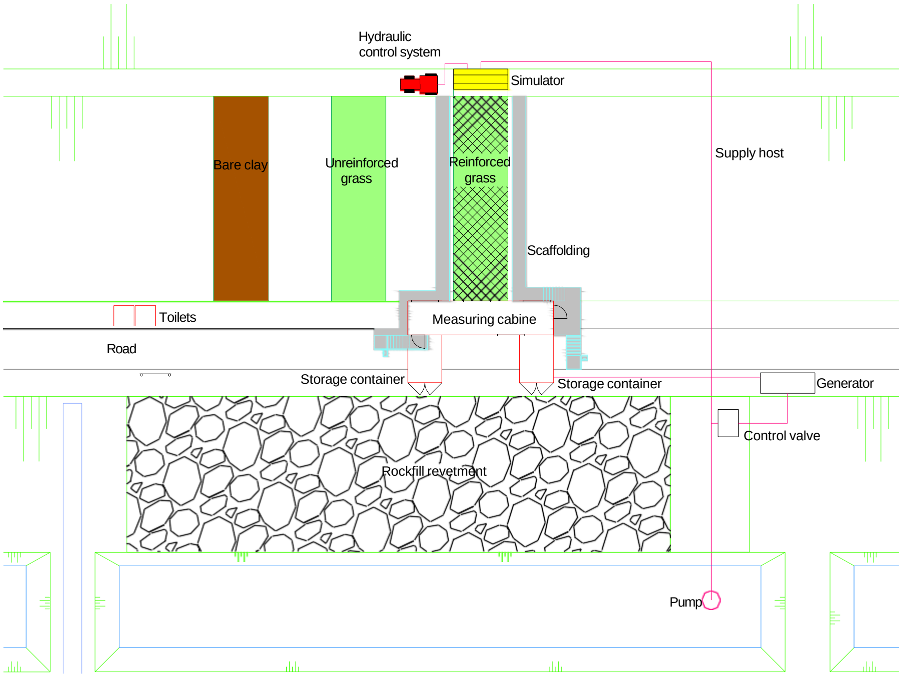


Figure 2.4 *Schematic top view of the test arrangement with the bare clay section on the left side (Akkerman et al., 2007).*

On June 13th, 2023, six samples of the clay on the slope were taken and sent to the laboratory of ESTP in Paris. The samples were taken on each side of the former test location, with two samples taken near to the crown of the dike, two samples in the middle of the slope and two samples close to the toe, above the road, as indicated in Figure 2.5. The samples were taken by driving a standard Shelby tube with an external diameter of 76.2 mm (3 inches) into the ground using a hand hammer.

Figure 2.5 Locations of the samples (Bennabi, 2023).

2.4.2 Lelystad

At a location near Lelystad, several wave overtopping tests have been carried out in Autumn 2023 on the landside slope of the main dike along Lake IJssel, see Figure 2.6. Some tests were carried out on ‘very well compacted clay’ and have been measured by photogrammetry by UC Louvain. One test was conducted on the boulder clay under that clay layer. From this test, laser scanner measurements are available for the initial and the final situation. Besides, six samples of the boulder clay were taken by Deltares at the locations indicated in Figure 2.7 on December 6th, 2023, and sent to ESTP to perform EFA tests. Results of these tests were reported in February 2024.

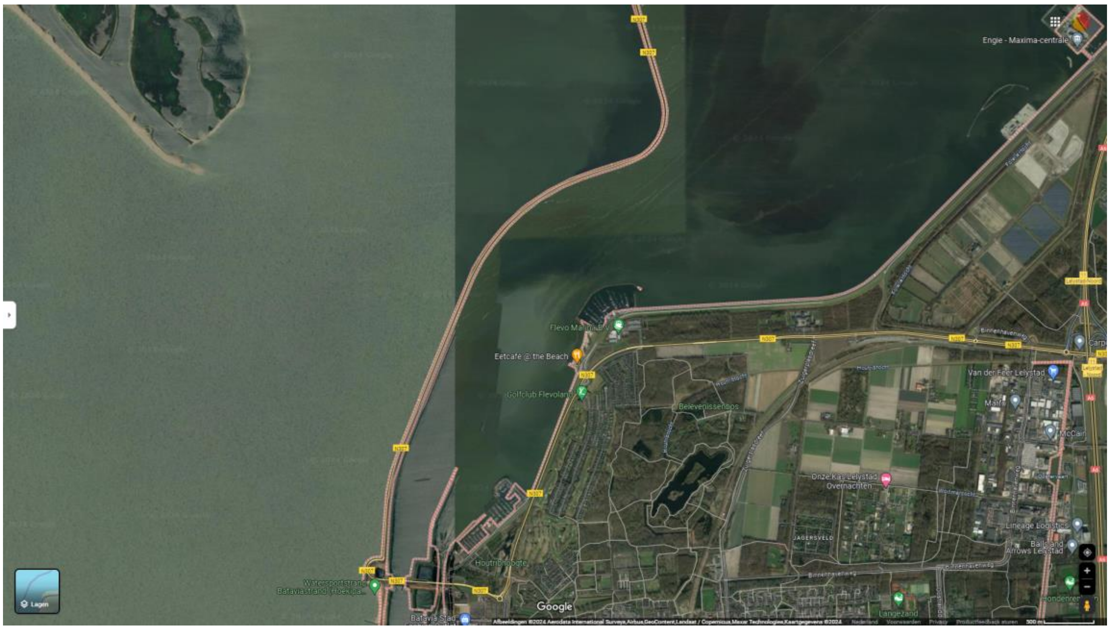


Figure 2.6 Overview of the area NE of Lelystad where the wave overtopping tests were carried out. The test location is a few hundred metres SW of the Engie – Maxima power plant in the upper right corner.

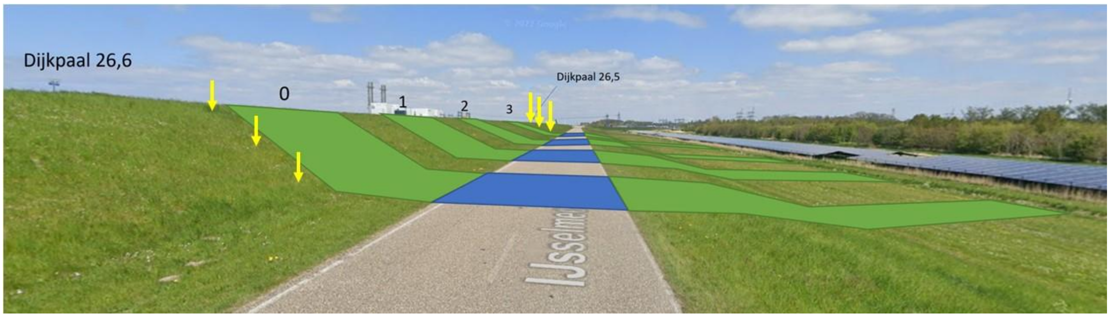


Figure 2.7 Locations of the test samples near Lelystad, indicated by the yellow arrows, relative to the four locations (0 – 3) of the wave overtopping tests and the chainage of the dike ('Dijkpaal 26.6' and 'Dijkpaal 26.5' – 100 m apart).

3 Validation of the model for clay erosion by wave overtopping

3.1 Introduction

The ISL model for overtopping erosion is applied to various test situations where the wave overtopping simulator was used to test the erodibility of bare clay on a slope. An important restriction is that in all cases evaluated, a grass sod down to approximately 20 cm from the original surface level had been removed prior to the tests. As observed, a significant amount of grass roots was still present, which likely influenced the outcome compared to a situation with bare clay only.

In Section 3.2 the data from the Hedwigepolder is analysed and the erosion parameters are calibrated for two of the tests. Section 3.3 describes the validation of the model for the Delfzijl data. Section 3.4 describes the approach for the Lelystad situation. The sensitivity of the model and the uncertainties are discussed in Section 3.5. Section 3.6 discusses the influence of including the clay cover on the probability of failure of the dike, compared to the present situation in the Netherlands where only the grass cover is considered.

3.2 Wave overtopping tests at Hedwigepolder – calibration and validation

3.2.1 Overview of available information

As part of the Interreg Polder2C's project, a series of wave overtopping experiments was carried out on the landside slope of the dike along the Hedwigepolder in the Southwest of the Netherlands. The set up of these experiments is described in §2.2 of Van Damme et al. (2023), the main results are given in §5.2 of the same report. In §5.1 of that report, results from Erosion Function Apparatus tests (EFA) and Jet Erosion Tests (JET) on samples taken in the vicinity of these experiments are given. Some additional information is given by Daamen et al. (2022) and Ebrahimi (2023). To facilitate understanding, some of the information is repeated in this section, supplemented with execution details not given in the above sources.

In total, five tests on 'bare clay' were carried out, divided over two parts of the landside slope as indicated in Figure 3.1. Before each test, the upper 20 cm of the test section, including the grass on top, was removed by an excavator. Note that the root system of the grass in this case reaches deeper than 20 cm. For subsequent tests on the same part, earlier test sections were covered to avoid additional erosion there.

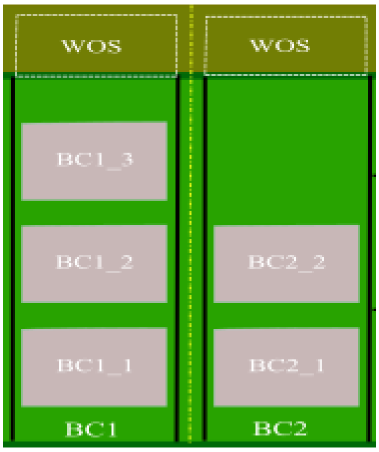


Figure 3.1 Schematic top view of tests on bare clay (WOS = Wave Overtopping Simulator).

The first three tests were carried out on the part indicated by ‘BC1’. For these tests, a series of regular waves was released from the Wave Overtopping Simulator, as shown in Figure 3.2. The tests were frequently interrupted to allow for measurements to be taken. Between each change in wave volume, a short pause was taken to allow the slope to become more or less dry, to enable the set of cameras used for subsequent photogrammetric analysis to measure the slope instead of a water surface. However, erosion pockets were not emptied from water, except for the final set of measurements at the end of each test. With a lower frequency (and a lower spatial resolution), measurements of the tested slope were taken by a hand-held DGPS system. At those instances, there was more time between the waves and the photogrammetric analysis was possible for a drier situation. Only a limited number of interruptions has been analysed, however, because of the time-consuming manual steps that appeared necessary during processing. Visual observations during the tests indicated that some erosion occurred even during the smallest series of waves (100 litres per metre of width of the dike per wave).

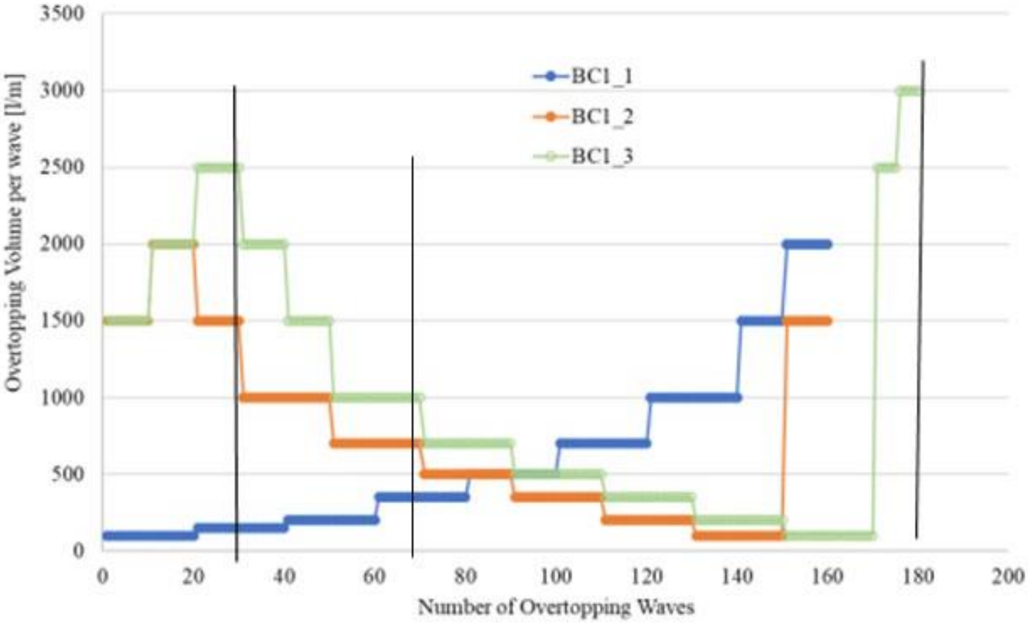


Figure 3.2 Distribution of the volume of the regular waves during the first three tests.

The fourth and fifth tests were carried out on the part indicated by ‘BC2’ in Figure 3.1. These tests simulated a two-hour storm for river conditions and sea conditions, respectively. The (randomly) generated waves are visualised in Figure 3.3. It should be noted that the wave overtopping simulator is limited by a minimum time between two releases, resulting in a minimum volume per wave for each test that depends on the average overtopping volume per unit of time (which is, in turn, equal to the flow rate by which the Wave Overtopping Simulator is filled). In Table 3.1 the characteristics of these tests are given (Daamen et al., 2022).

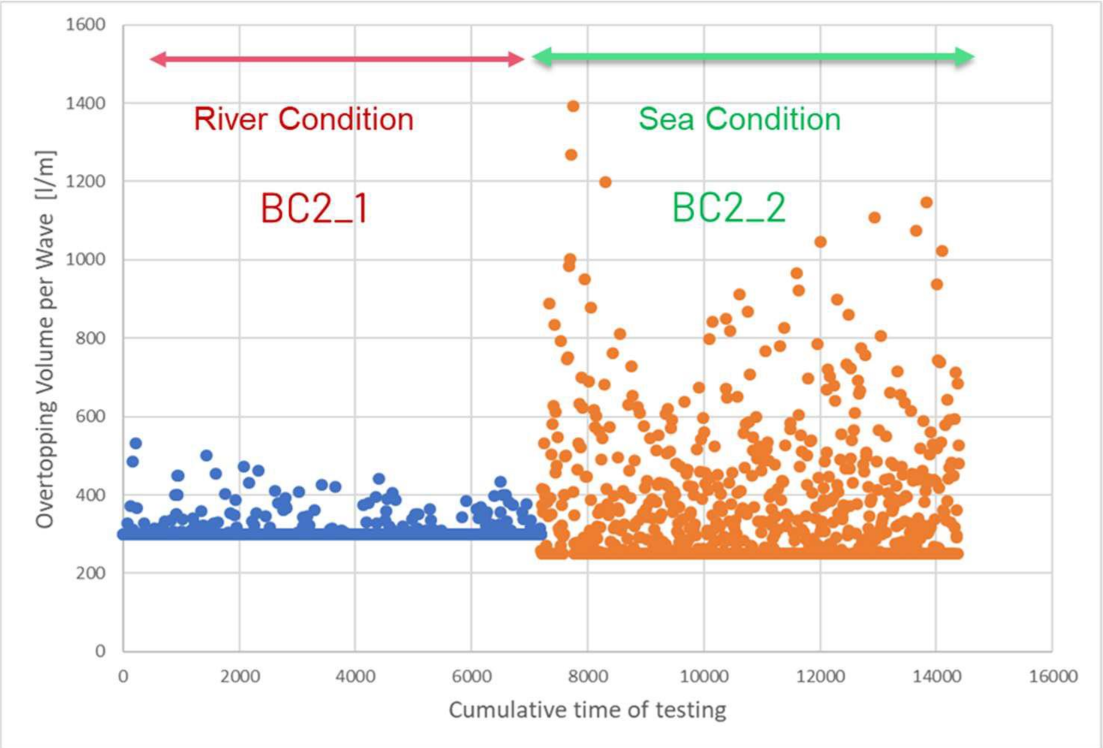


Figure 3.3 Overtopping volume per wave for 4th test (BC2_1) and 5th test (BC2_2).

Table 3.1 Characteristics of test 4 (BC2_1) and test 5 (BC2_2).

Test	4 (BC2_1)	5 (BC2_2)
Significant wave height H_s [m]	0.5	1.0
Average flow q [l/s/m]	60	50
Freeboard R_c [m]	0.05	0.68
Storm duration t_{storm} [hours]	2	2
Number of overtopping waves N_{ow} [-]	3388	1750
Probability of wave overtopping P_{ov} [-]	0.992	0.725

During these two tests, irregular interruptions took place to measure under semi-dry conditions. Roughly halfway test 4, these interruptions became significantly longer, to have more time for the erosion holes to drain. This decision was taken at the test site as soon as it became clear that a sixth test would not be possible within the available timeframe.

Figure 3.4, Figure 3.5 and Figure 3.6 show an impression of the tests and the final situations after the series of waves. Generally, the final situation showed a lot of bare roots (the clay around them being washed away), with a few deeper holes. The third test (BC1_3) was an exception: here, the erosion remained more or less evenly distributed over the whole section. Further details on the erosion during each test are given in Table 3.2, while Figure 3.7 shows the eroded volume (corrected for the tested area) as a function of the cumulative wave overtopping volume for each test.

In each test, the planned series of waves could be run before the erosion had progressed through the entire clay layer on top of the sand volume inside the dike. The soil investigations prior to the tests revealed a thickness of the clay layer of 0.85 to 1.4 m. Considering the removal of the upper 20 cm before the start of the test and 75 cm erosion during the 4th test, the final margin to the sand was likely to be small. Once the sand layer has been reached, the erosion process changes and becomes more rapid.

Figure 3.4 Impression of execution of first test (left) and composed top view of final situation (right).

Figure 3.5 Final situation at the end of test 4 (BC2_1).

Figure 3.6 Final situation at the end of test 5 (BC2_2).

Table 3.2 Overall performance of tests on bare clay (after Ebrahimi, 2023).

Test	**1**	**2**	**3**	**4**	**5**
Total wave overtopping volume [m^3]	380	488	721	1730	1440
Total area [m^2]	13.0	10.8	12.6	9.9	12.92
Total eroded volume [m^3]	0.95	0.79	1.52	1.62	1.75
Average erosion depth [m^3/m^2] × 10^2	7.36	7.34	12.04	16.34	13.55
Maximum erosion depth based on close-range photogrammetry [cm]	64	36	34	75	55

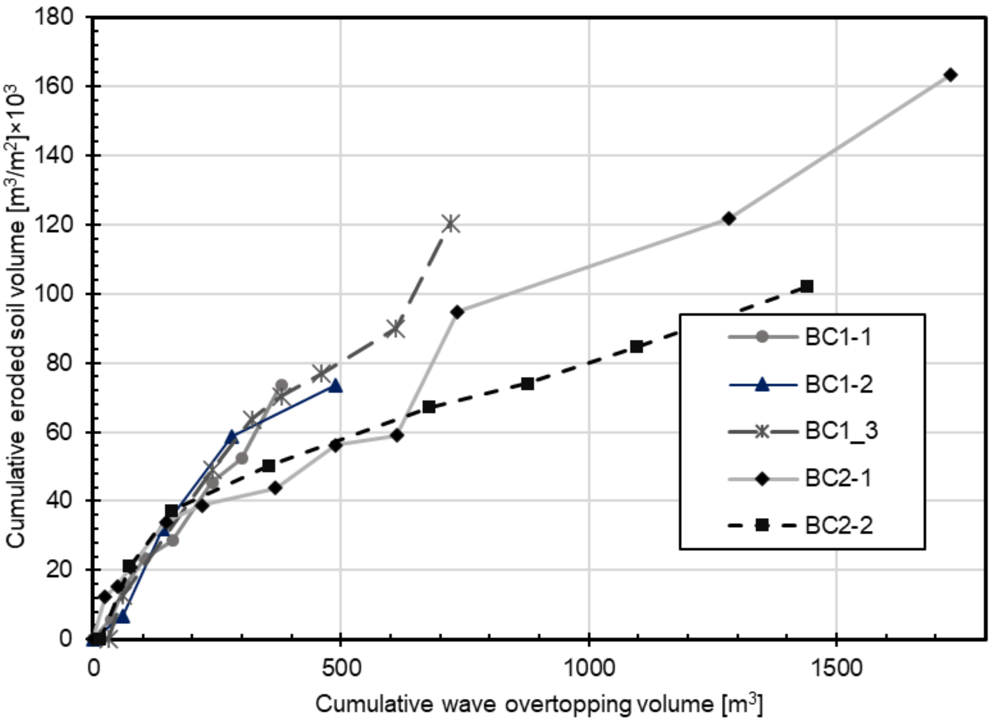


Figure 3.7 Cumulative eroded soil volume per unit area during all five tests (Ebrahimi, 2023).

The results from EFA and JET tests for the Hedwigepolder as given by Van Damme et al. (2023) are repeated in Annex D. For the EFA tests, the reported critical shear stress τ_c ranges from 0.19 to 0.47 Pa, while the reported erodibility coefficient K_d ranges from 1.86 to 15.00 cm^3/Ns. It should be noted that these EFA tests focussed on the initial erodibility. For the JET tests, τ_c ranged from 36 to 72 Pa (with a confidence interval of 19 to 89 Pa) and K_d ranged from 5.2 to 110 cm^3/Ns (with a confidence interval of 2.8 to 130 cm^3/Ns).

Between the different test types, the reported critical stresses differ by two orders of magnitude while the erodibility coefficient differs by one order of magnitude. For flows resulting in a shear stress exceeding the maximum critical shear stress, this does not necessarily lead to different results, yet for flows resulting in shear stresses between the minimum and maximum critical shear stresses, different results are inevitable. In case of shear stresses below the minimum critical shear stress, no erosion will take place in any case.

Because of the physical meaning of the critical shear stress, the observation mentioned right above Figure 3.2 about the smallest waves of 100 litres per metre per wave already causing some erosion implies that the critical shear stress in the field was not very high, favouring the EFA test results above the JET test results. Note that the value of the erodibility coefficient should always be evaluated in combination with the value of the critical shear stress.

3.2.2 Approach to the calibration of erosion parameters for the Hedwigepolder

For the calibration of the erosion parameters used in the model, τ_c and K_d, at least two reliable measurements of the erosion depth after a certain period of loading are required.

For test 1, 2 and 3, there is no measure of the erosion caused by a single set of regular waves having the same volume each because of the few intermediate analyses. For an efficient procedure, the code would need to be modified to process various series of regular waves with different volumes before a proper analysis would be possible for the whole test and parts thereof. Therefore, it was decided to focus on test 4 and 5.

The most reliable measurements available are the erosion depths at the end of these tests. Intermediate values are also available for these tests, yet these are less reliable because the erosion holes were not fully drained for those values. One would expect this to lead to a systematic underestimation of the intermediate measured erosion depth. Considering the curve of the fourth test, BC2_1, in Figure 3.7, this does not seem to be the case. However, this graph only shows the eroded volume, not the depth of the deepest erosion hole and the erosion process tends to be less evenly spread in course of time with regards to the maximum erosion depth that is reached, with a more rapid growth over time (besides, the location of the deepest hole may also change over time). Thus, the most valuable and reliable measurements are those at the end of a test. Moreover, the parameters should be representative of the whole slope, not only a smaller part of it, so using these two measurements should both yield a reliable solution.

In this context, the spatial variation in the erosion in the field test is considerable over a distance larger than the size of the small-scale tests. This could imply that generally a small-scale test sample is not likely to be taken at a weak spot. Yet, the load conditions are also influenced on a larger scale than the size of the small-scale tests.

3.2.3 Calibration for Hedwigepolder test section 4 (irregular waves)

For test section 4 (BC2_1), an erosion depth of 0.75 m was measured at the end of the test. The executable of the OTE2C$_{ISL}$ model, with a friendly user interface, was used to determine the erosion depth as calculated by the model.

The following parameters were used:

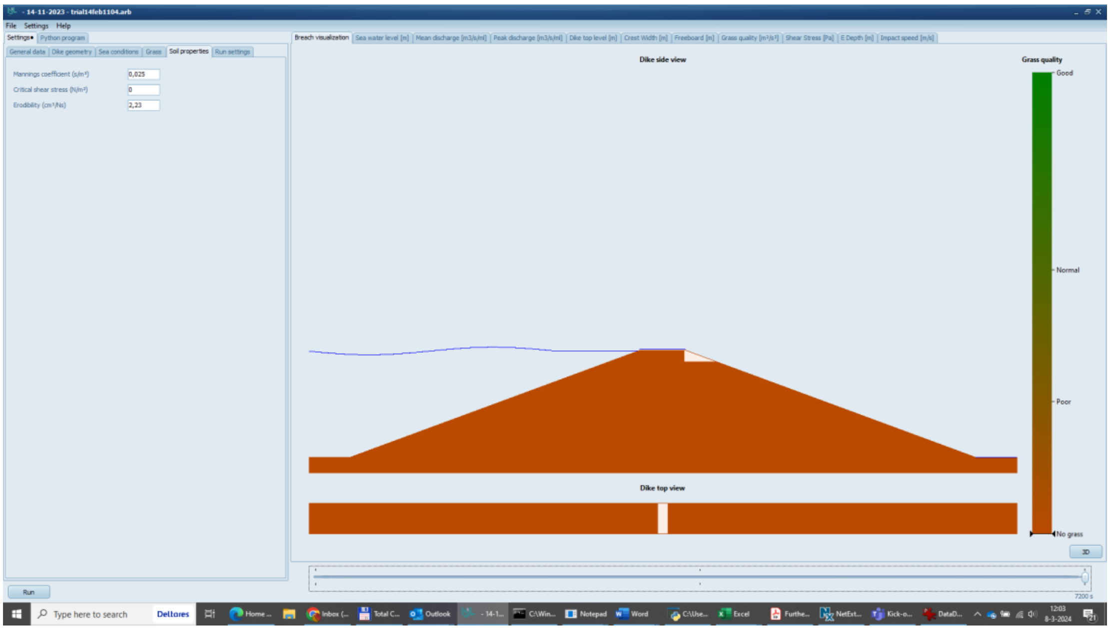
- General data:
  - Start time: 0 (s) (unchanged).
  - End time: 7200 (s) (two hours of storm simulated by the test).
  - Time steps: 2 (s) (default value is 120 (s)).
- Dike geometry:
  - Initial dike height: 7 (m).
  - Initial crest level: 8 (m above datum).
  - Crest width: 3 (m) (unchanged default value).
  - Crest length: 100 (m) (unchanged default value, irrelevant for the current analysis).
  - Seaside slope (H/V): 2.7.
  - Landside slope (H/V): 2.7.
- Sea conditions:
  - Mean sea level: 7.95 (m above datum).
  - High tide level: 7.95 (m above datum).
  - High tide time: 14200 (s) (unchanged default value, irrelevant for the current analysis).
  - Significant wave height: 0.5 (m).
  - Wave period: 2.108 (s) (calculated from the three lower rows in Table 3.1).
  - Irregular waves: Yes.
- Grass parameters: irrelevant for the current analysis.
- Soil properties:
  - Mannings coefficient: 0.025 (s/m^3) (unchanged default value).
  - Critical shear stress: *variable, see* Table 3.3.
  - Erodibility: *variable, see* Table 3.3.
- Run settings: irrelevant for the current analysis.

The values of the critical shear stress and the erodibility coefficient were varied as indicated in Table 3.3, where also the calculated erosion depth after two hours is given. This was determined by trial and error (the calculation time is limited, even with the small time steps taken), the first few rows of the table indicate how close the target value of 0.75 (m) could be approached for the given value of the critical shear stress and an erodibility coefficient expressed in ‘only’ two digits. The target value of 0.75 m is the maximum local measured depth in the test section. This value was chosen as target value to enable a comparison with the experimental findings for the same loading conditions and time.

Table 3.3 Calculated erosion depth for the conditions of test 4, for various combinations of τ_c and K_d.

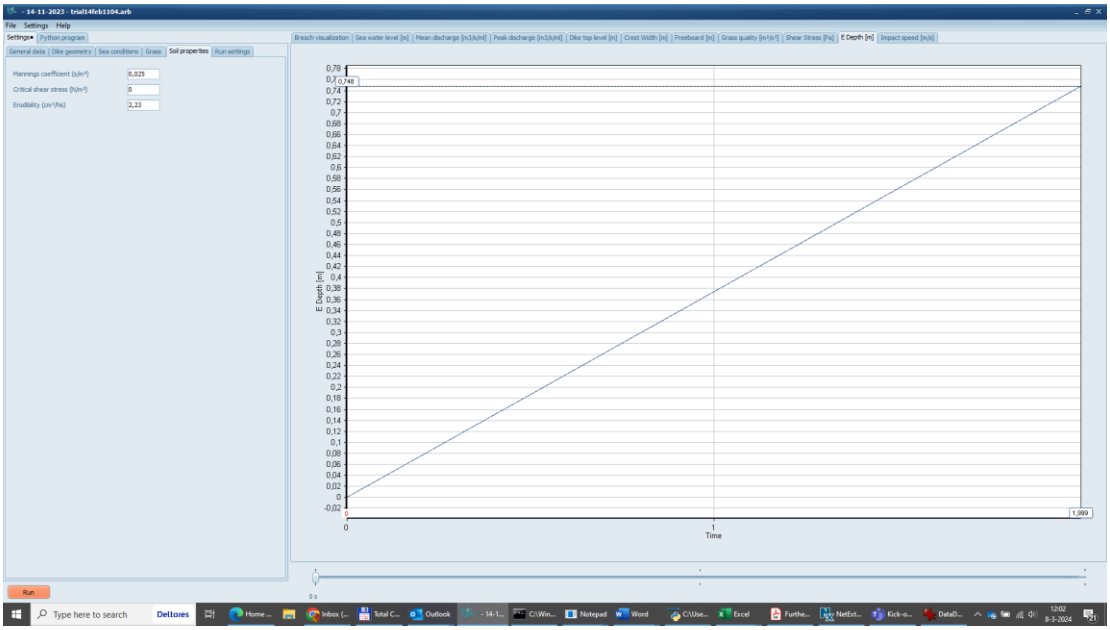
τ_c [Pa]	K_d [cm^3/Ns]	Calculated erosion depth [m]
0	2.23	0.748
0	2.24	0.752
0.1	2.23	0.747
0.1	2.24	0.751
0.2	2.24	0.750
0.5	2.25	0.751
1	2.26	0.751
2	2.28	0.750
3	2.30	0.749
5	2.35	0.749
10	2.48	0.750
15	2.62	0.750
20	2.77	0.749
30	3.13	0.749
50	4.13	0.751
75	6.16	0.751
90	8.03	0.750
100	9.75	0.750
150	33.10	0.749
200	100.48	0.751

The executable offers a graphic user interface, visualising the output. By drawing a slider at the bottom of the window, a trip through time of the output can be made. Slightly confusing is the fact that this slider has a scale in seconds, while the horizontal axis right above it is divided in hours. Output variables that are available are a graphic representation of the dike, the water level and the erosion profile (see Figure 3.8 and Figure 3.13), the sea water level, the mean discharge, the peak discharge, the crest level (labelled as ‘dike top level’), the crown width (labelled as ‘crest width’), the freeboard, the grass quality, the shear stress, the erosion depth (see Figure 3.9 and Figure 3.12) and the impact speed (see Figure 3.10, Figure 3.11 and Figure 3.14).



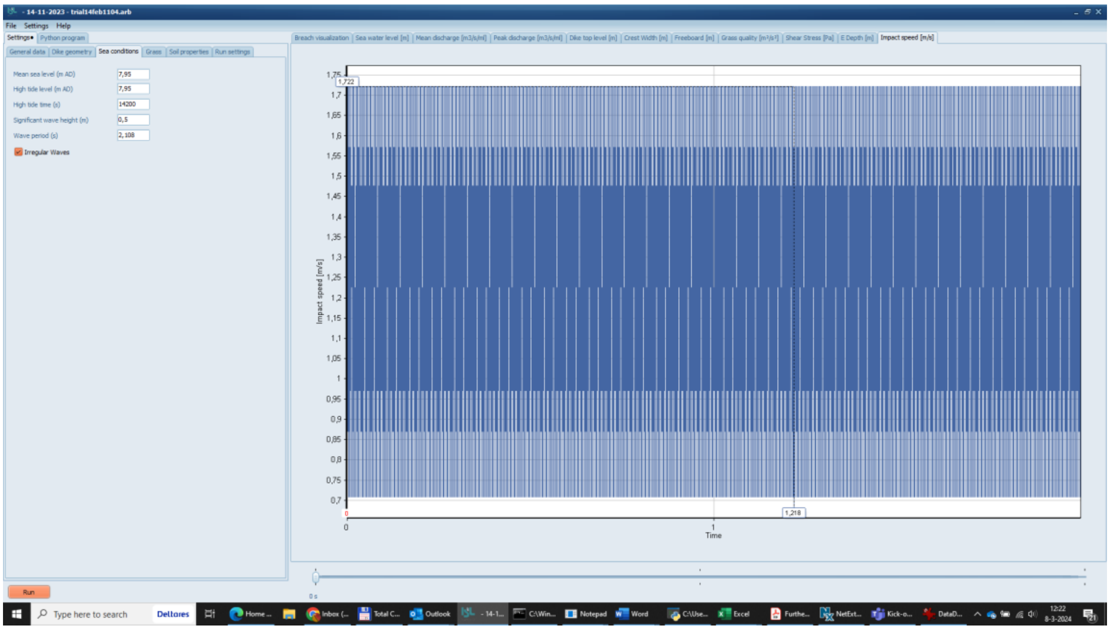
Mannings coefficient (s/m^3) 0,025
Critical shear stress (N/m^2) 0
Erodibility (cm^3/Ns) 2,23

Figure 3.8 Graphic representation of the dike at t = 7200 (s), with an erosion depth of about 0.75 m, with τ_c = 0 Pa and K_d = 2.23 cm^3/Ns (test 4). The location of the initial damage is the point of impact on the landside slope, in these calculations typically right after the crown. The headcut advance is calculated as detailed by Van Hoven & Wopereis (2022).



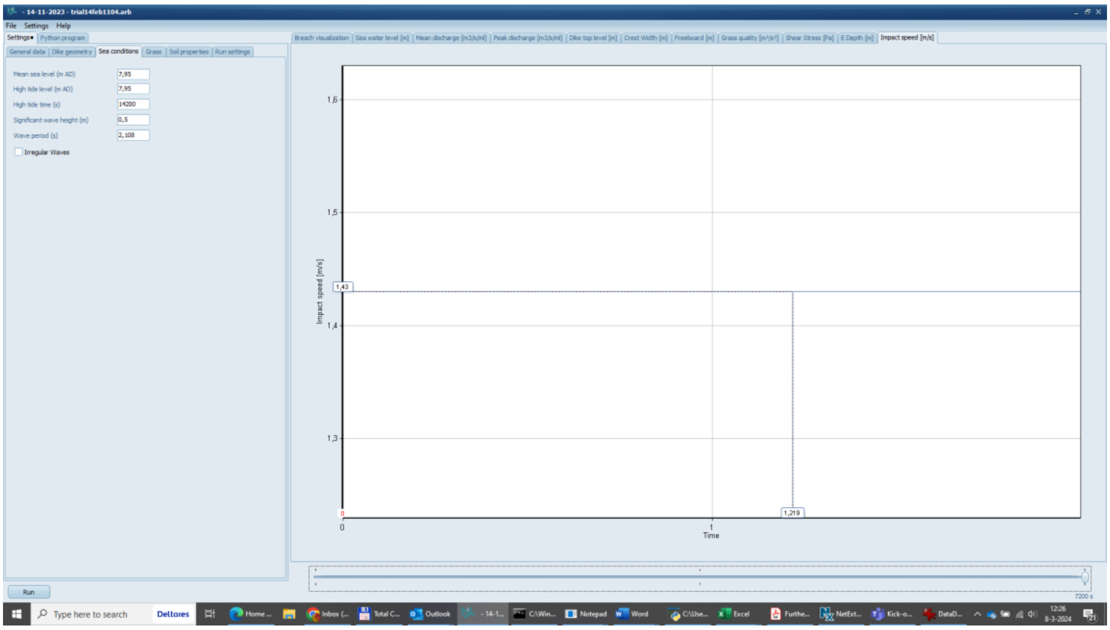
Mannings coefficient (s/m^3) 0,025
Critical shear stress (N/m^2) 0
Erodibility (cm^3/Ns) 2,23

Figure 3.9 Development of the erosion depth over time, with a final erosion depth of about 0.75 m (test 4).



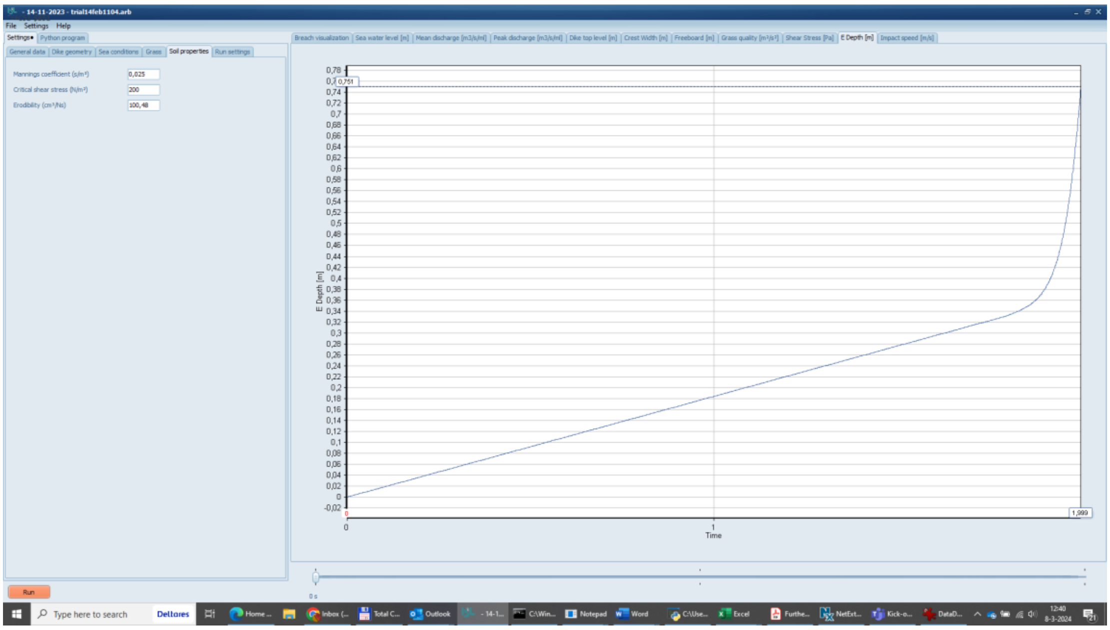
Mean sea level (m AD) 7,95
High tide level (m AD) 7,95
High tide time (s) 14200
Significant wave height (m) 0,5
Wave period (s) 2,108
☑ Irregular Waves

Figure 3.10 Impact speed throughout the 2 simulated hours with the option 'irregular waves', values varying between 0.71 and 1.722 m/s.



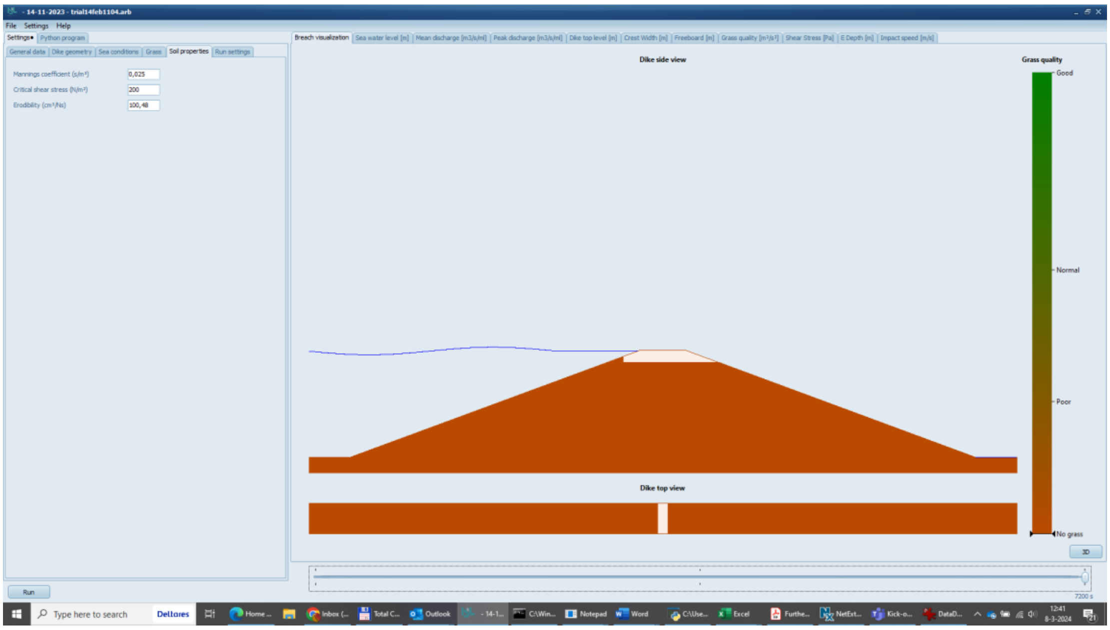
Mean sea level (m AD) 7,95
High tide level (m AD) 7,95
High tide time (s) 14200
Significant wave height (m) 0,5
Wave period (s) 2,108
☐ Irregular Waves

Figure 3.11 Impact speed throughout the 2 simulated hours with the option 'regular waves' (constant value of 1.43 m/s).



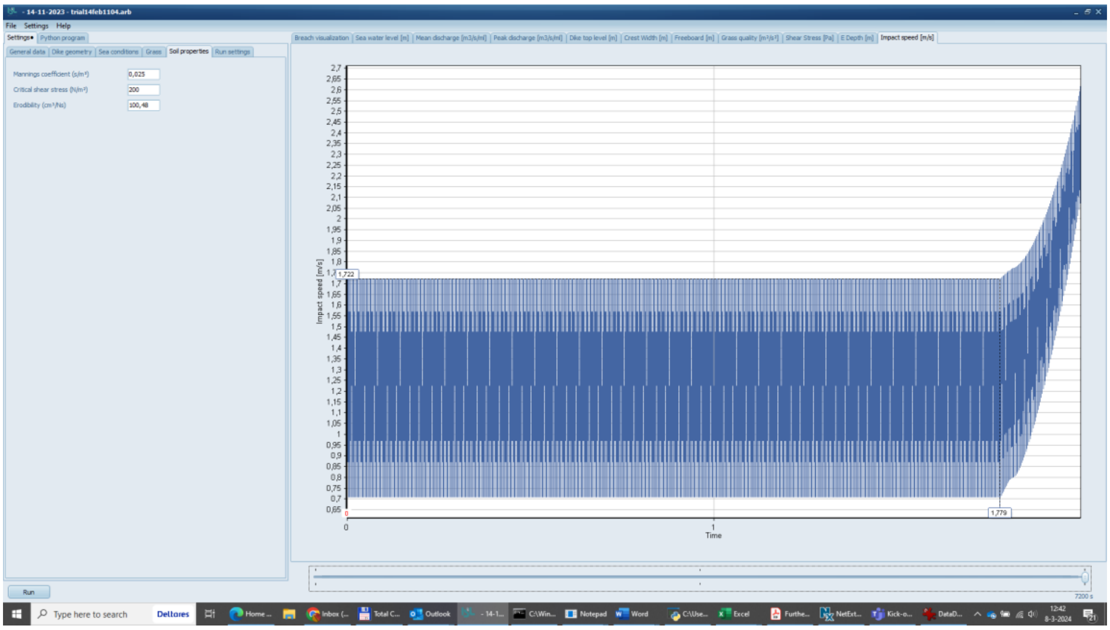
Mannings coefficient (s/m³) 0,025
Critical shear stress (N/m²) 200
Erodibility (cm³/Ns) 100,48

Figure 3.12 Development of the erosion depth over time, with a final erosion depth of 0.751 m with τ_c = 200 Pa and K_d = 100.48 cm^3/Ns (test 4).



Mannings coefficient (s/m³) 0,025
Critical shear stress (N/m²) 200
Erodibility (cm³/Ns) 100,48

Figure 3.13 Graphic representation of the dike at t = 7200 s, with a final erosion depth of 0.751 m with τ_c = 200 Pa and K_d = 100.48 cm^3/Ns (test 4).


- 14-11-2023 - trial14feb1104.arb

Mannings coefficient (s/m³) 0,025
Critical shear stress (N/m²) 200
Erodibility (cm³/Ns) 100,48

Figure 3.14 Impact speed increasing once crest becomes lower, same situation as the previous figure.

The last three figures above refer to a situation where the crown recedes faster than the increase in the erosion depth.

Figure 3.10 casts some doubt how irregular the calculated waves are. In comparison with Figure 3.3, the distribution seems much more regular. On the other hand, the regular waves of Figure 3.11 are even more regular. However, the overall impact is different: with regular waves and all other parameters unchanged, for τ_c = 0 Pa and K_d = 2.23 cm^3/Ns an erosion depth of 0.904 m is obtained and for t_c = 10 Pa and K_d = 2.48 cm^3/Ns an erosion depth of 0.922 m, instead of 0.75 m.

3.2.4 Calibration for Hedwigepolder test section 5 (irregular waves)

For test section 5 (BC2_2), an erosion depth of 0.55 m was measured at the end of the test. The applied procedure is the same as for test 4, yet with the following modifications of the sea conditions:

- Mean sea level: 7.32 (m above datum).
- High tide level: 7.32 (m above datum).
- Significant wave height: 1.0 (m).
- Wave period: 2.983 (s).

Similar to the previous section, the values of the critical shear stress and the erodibility coefficient were varied as indicated in Table 3.4, where also the calculated erosion depth after two hours is given. Here, the target value is 0.55 m. The target value of 0.55 m is the maximum local measured depth in the test section. This value was chosen as target value to enable a comparison with the experimental findings for the same loading conditions and time.

Table 3.4 Calculated erosion depth for the conditions of test 5, for various combinations of τ_c and K_d.

τ_c [Pa]	K_d [cm^3/Ns]	Calculated erosion depth [m]
0	3.24	0.550
0.1	3.24	0.550
0.2	3.24	0.549
0.2	3.25	0.551
0.5	3.25	0.549
0.5	3.26	0.551

τ_c [Pa]	K_d [cm^3/Ns]	Calculated erosion depth [m]
1	3.26	0.549
1	3.27	0.551
2	3.29	0.549
2	3.30	0.551
3	3.32	0.550
5	3.37	0.549
10	3.52	0.550
15	3.68	0.550
20	3.84	0.550
30	4.19	0.549
50	5.08	0.550
75	6.69	0.550
90	8.03	0.550
100	9.13	0.550
150	19.00	0.550
200	47.9	0.550

3.2.5 ‘Optimal values’ of t_c and K_d from Hedwigepolder test sections 4 and 5

From comparison of Table 3.3 and Table 3.4, it follows that for both tests, the measured erosion depth is calculated for t_c = 90 Pa and K_d = 8.03 cm^3/Ns, assuming similar loading conditions on both test sections, apart from the variation in loading characteristics already specified (and applied during the field tests).

When comparing these values to the results obtained from the EFA and JET tests, as presented in Annex D, the difference is striking, especially for the EFA tests. The calibrated value for the critical shear stress, in other (simpler) words: the threshold below which no erosion occurs, is much higher than for the EFA tests (90 Pa versus 0.19 to 0.47 Pa) and it also does not fit well with the observation that even for relatively small waves (100 l/m) some erosion occurred.

3.2.6 Validation using values from EFA and JET tests

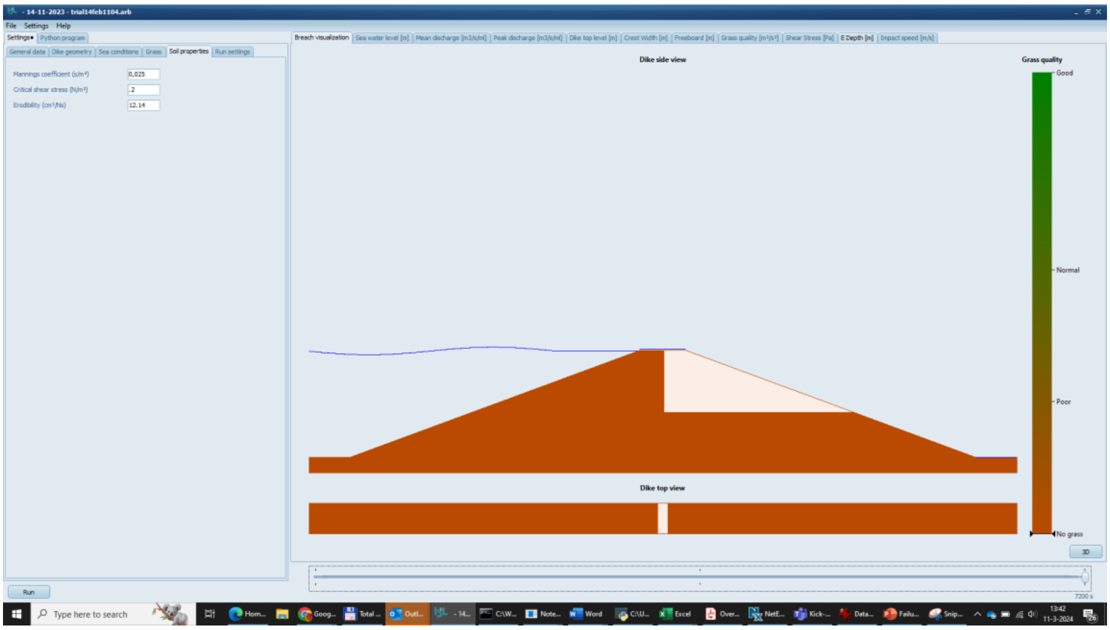
The four sets of combinations of the critical shear stress and the erodibility coefficient from the EFA tests as given by Table_ D.1.1 and the two combinations for these parameters from the JET tests on Section X and Section XI as given by Table_ D.2.1 have been applied to calculate the erosion depths for the conditions of tests 4 and 5. The results are given in Table 3.5.

Table 3.5 Erosion depths calculated by OTE2C$_{ISL}$ for various combinations of τ_c and K_d for the conditions of tests 4 and 5.

Origin of parameters	τ_c [Pa]	K_d [cm^3/Ns]	E_d for Test 4 [m]	E_d for Test 5 [m]
EFA sample 1	0.2	12.14	4.064	2.058
EFA sample 2	0.19	15.00	5.023	2.544
EFA sample 3	0.45	1.86	0.621	0.315
EFA sample 5	0.47	6.82	2.277	1.153
JET section X	63	110	Complete failure	Complete failure
JET section XI	72	24	3.077	2.045

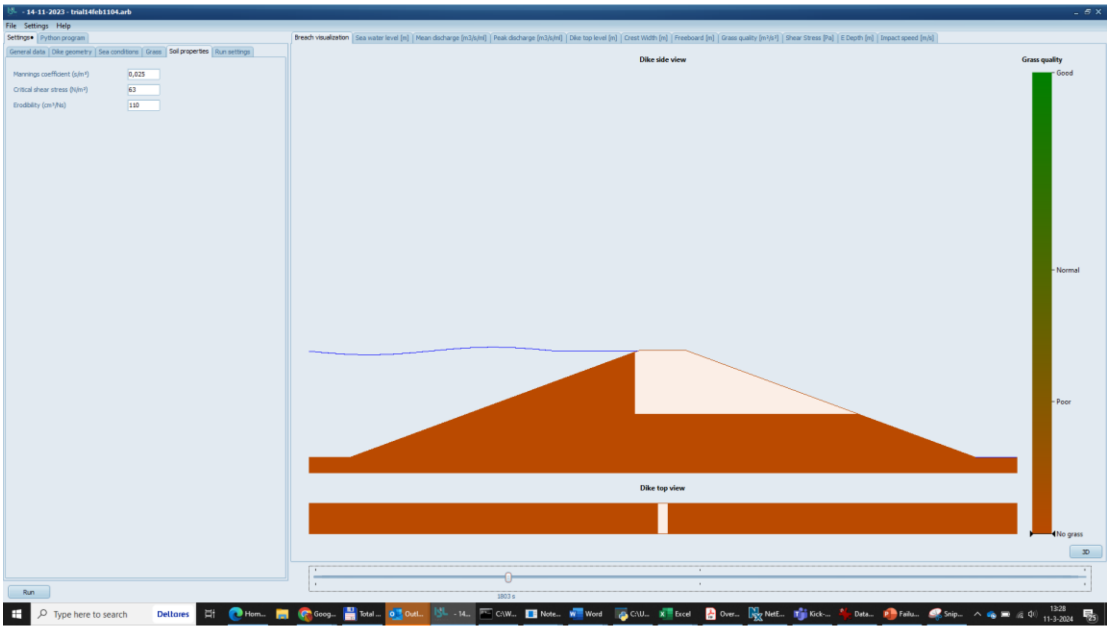
In most cases, the calculated erosion depths are clearly more than measured. The only exception is found for EFA sample 3, where the calculated erosion depths are 17% and 43% smaller, respectively.

Figure 3.15 and Figure 3.16 show the presented erosion profiles for test 4 for the first and the fifth data row in Table 3.5. For the latter, the entire crown is already gone after a quarter of the test period and full failure is calculated shortly after.


- 14-11-2023 - trial14feb1104.arb

Mannings coefficient (s/m³) 0,025
Critical shear stress (N/m²) .2
Erodibility (cm³/Ns) 12.14

Figure 3.15 Erosion profile as presented for EFA sample 1 for test 4, after the full test period of two hours.


- 14-11-2023 - trial14feb1104.arb

Mannings coefficient (s/m³) 0,025
Critical shear stress (N/m²) 63
Erodibility (cm³/Ns) 110

Figure 3.16 Erosion profile as presented for JET section X for test 4, after one quarter of the test period only.

3.3 Wave overtopping test at Delfzijl (ComCoast) – validation

3.3.1 Data from the wave overtopping tests

The test started with a few small initial waves, reported as ‘short-duration wave overtopping at 0.1 l/s/m’ (Akkerman et al., 2007:59). The resulting surface of the slope is shown in Figure 3.17.

Figure 3.17 Bare clay surface after a few small waves, showing a depression in the middle of the slope and a few small erosion pits (Akkerman et al., 2007).

The next test stage was a simulated storm of 6 hours with an average wave overtopping volume of 1 litre per second per metre width, executed in parts of 2 hours with measurements in between. An impression of this stage is shown in Figure 3.18.

Figure 3.18 Situation during overtopping of 1 l/s/m on bare clay. The biggest wave shown here had a volume of 1 m^3 per m width (Akkerman et al., 2007).

The third test stage comprised an average wave overtopping volume of 5 litres per second per metre width for 6 hours with breaks every 2 hours. An impression of this stage is shown in Figure 3.19.

Figure 3.19 Situation during overtopping of 5 l/s/m on bare clay. The biggest wave shown here had a volume of 2.0 m^3 per m width (Akkerman et al., 2007).

The fourth and last test stage comprised an average wave overtopping volume of 10 litres per second per meter width, again for 6 hours with breaks every 2 hours. An impression is shown in Figure 3.20. Figure 3.21 shows the final situation after dewatering.

Figure 3.20 Situation during overtopping of 10 l/s/m on bare clay. The biggest wave shown here had a volume of 2.5 m^3 per m width (Akkerman et al., 2007).

Figure 3.21 Final situation after wave overtopping tests on bare clay and dewatering (Akkerman et al., 2007).

The erosion profile was measured in a 1 m x 1 m grid, at locations with significant erosion in a 0.5 m x 0.5 m grid. The combined profile of the most extreme erosion along the slope is shown in Figure 3.22. The maximum values are summarized in Table 3.6.

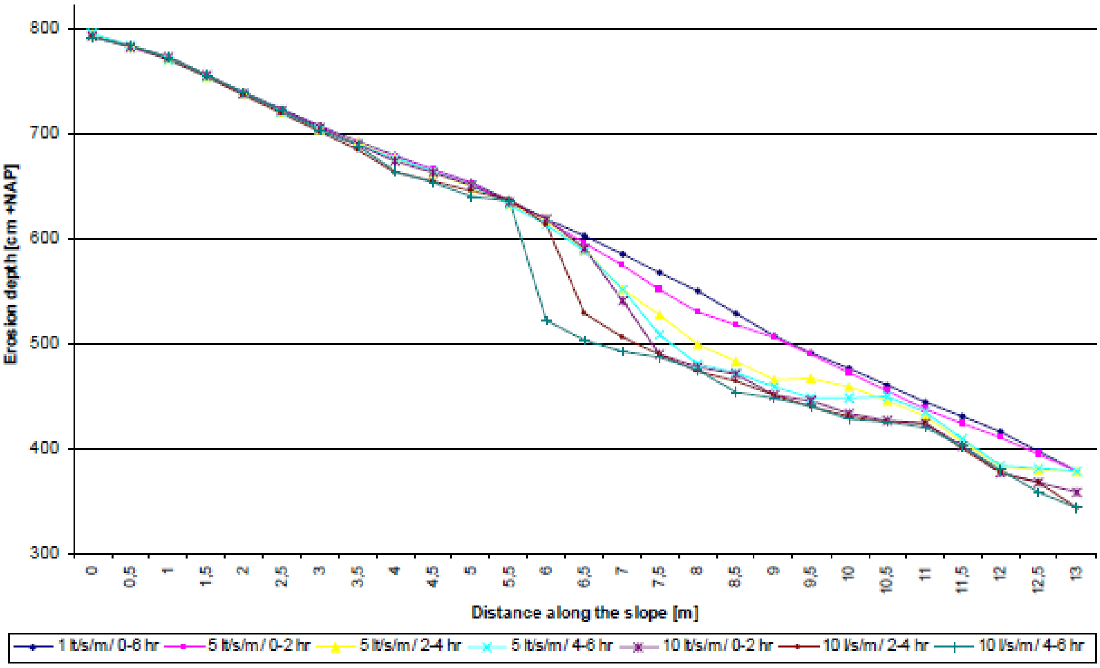


Figure 3.22 Measured erosion (highest values of both holes) along the slope for the test series on bare clay (Akkerman et al., 2007).

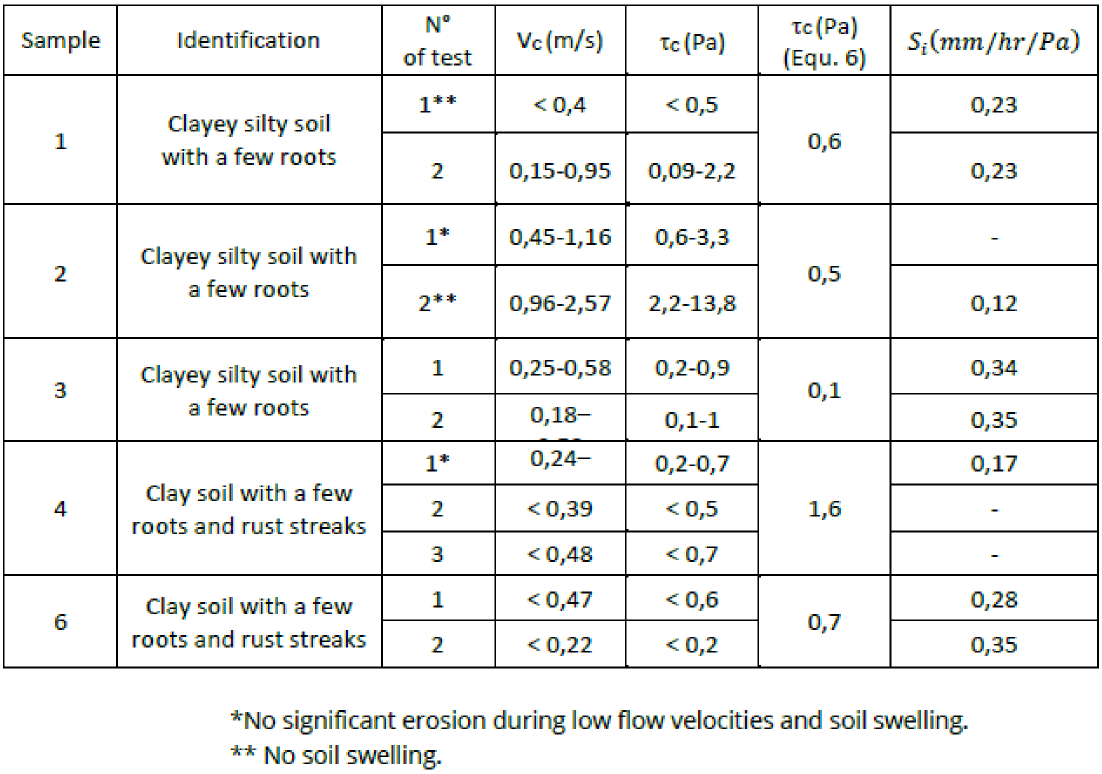
Table 3.6 Maximum recorded vertical erosion depths at various stages of the Delfzijl test on bare clay relative to the erosion after the 1 l/s/m stage.

Stage	Maximum vertical erosion depth [cm]	Length along slope [m]
5 l/s/m after 2 hours	18.88	8.24
5 l/s/m after 4 hours	52.11	8.24
5 l/s/m after 6 hours	69.49	8.24
10 l/s/m after 2 hours	76.28	7.73
10 l/s/m after 4 hours	79.30	7.24
10 l/s/m after 6 hours	98.19	6.73

3.3.2 Results of the EFA tests

One of the five Shelby tubes appeared to be damaged, the results of the EFA tests on the other five samples are given in Table 3.7. The values in the last column need to be divided by 3.6 to convert to [cm^3/Ns] as used for K_d elsewhere in this report (cf. Table 3.9)

Table 3.7 Results of the EFA tests on Delfzijl samples: critical flow velocity V_c, critical shear stress τ_c and initial erodibility S_i (=K_d) (Bennabi, 2023).



Sample	Identification	N° of test	Vc (m/s)	τc (Pa)	τc (Pa) (Equ. 6)	$S_i (mm/hr/Pa)$
1	Clayey silty soil with a few roots	1**	< 0,4	< 0,5	0,6	0,23
		2	0,15-0,95	0,09-2,2		0,23
2	Clayey silty soil with a few roots	1*	0,45-1,16	0,6-3,3	0,5	-
		2**	0,96-2,57	2,2-13,8		0,12
3	Clayey silty soil with a few roots	1	0,25-0,58	0,2-0,9	0,1	0,34
		2	0,18–	0,1-1		0,35
4	Clay soil with a few roots and rust streaks	1*	0,24–	0,2-0,7	1,6	0,17
		2	< 0,39	< 0,5		-
		3	< 0,48	< 0,7		-
6	Clay soil with a few roots and rust streaks	1	< 0,47	< 0,6	0,7	0,28
		2	< 0,22	< 0,2		0,35

*No significant erosion during low flow velocities and soil swelling.
** No soil swelling.

3.3.3 Calibration and validation of the OTE2C$_{ISL}$ model

Both the validation and the calibration of the model can be carried out in a way similar to the approach followed in the previous section.

An important choice concerns which situation is chosen. Taking the final situation is a bit complicated, because this was preceded by two different sets of wave conditions and because a different erosion pit developed to be partly the dominant erosion pit. By taking the result of the 1 l/s/m stage as the base line, the three different parts of the 5 l/s/m stage may be used for the analysis, i.e. by calculating after 2 hours in total, after 4 hours in total and after the full period of 6 hours in total.

For this case, the following input for the model needs to be modified from the data given in §3.2.3 into:

- General data:
  - End time: 7200 / 14400 / 21600 (s).
  - Time steps: 5 (s).
- Dike geometry:
  - Initial crest level: 8 (m above datum) (not known, but relevant in combination with the sea conditions to ensure the freeboard of 4 m (Van der Meer, 2007)).
  - Seaside slope (H/V): 4 (Van der Meer, 2007).
  - Landside slope (H/V): 3 (Van der Meer, 2007).
- Sea conditions:
  - Mean sea level: 4 (m above datum).
  - High tide level: 4 (m above datum).
  - Significant wave height: 2.0 (m) (Van der Meer, 2007).
  - Wave period: 5.7 (s) (Van der Meer, 2007).

The results for the calibration are presented in Table 3.8. The model has applied with the above data and the value of the critical shear stress mentioned and by iteration the value for the erodibility coefficient was modified until the target value for the erosion depth as mentioned in the header of the table was found. Unlike the Hedwige case, no single combination of the two parameters is found that fits two test periods.

Table 3.8 Calibration of the erodibility parameters for the Delfzijl test with an average wave overtopping discharge of 5 l/s/m.

0 – 2 h (target value for erosion depth: 0.189 m)		**0 – 4 h (target value for erosion depth: 0.521 m)**		**0 – 6 h (target value for erosion depth: 0.695 m)**	
τ_c [Pa]	**K_d [cm^3/Ns]**	**τ_c [Pa]**	**K_d [cm^3/Ns]**	**τ_c [Pa]**	**K_d [cm^3/Ns]**
0	99.0	**0**	136.2	**0**	121.1
0.1	99.0	**0.1**	136.7	**0.1**	121.5
0.3	99.6	**0.3**	137.5	**0.3**	122.2
0.5	100.3	**0.5**	138.4	**0.5**	123
1	102	**1**	140.5	**1**	125
2	105	**2**	145	**2**	128.9
5	116	**5**	160	**5**	142.3
10	139	**10**	191.5	**10**	170.3
30	363	**30**	499.5	**30**	444
50	2380	**50**	3097	**50**	2257

For the situation with τ_c = 0 Pa, with a K_d around 100 cm^3/Ns and also a peak shear stress of around 50 Pa, one would expect a peak erosion rate of 5 mm/s. Of course, this peak is not present continuously, see §2.3.2 and Figure 2.1 in particular. Yet, 5 mm/s, if continuously, would lead to an erosion depth of 36 m in 2 hours, and the 0.189 m of erosion depth is only about 0.5% of that, which seems a bit unlikely. This matter should be investigated further.

The erodibility parameters presented in Table 3.7 have been applied to calculate the erosion depth after 2, 4 and 6 hours. For this case, the erosion depth as calculated with the results from the EFA tests are presented in Table 3.9 (results are presented in three digits by OTE2C$_{\mathrm{ISL}}$).

Table 3.9 *Validation of the erodibility parameters for the Delfzijl test found by EFA tests with an average wave overtopping discharge of 5 l/s/m.*

Sample	τ_c [Pa]	K_d [cm^3/Ns]	Calculated erosion depth [m]		
			0 – 2 h	0 – 4 h	0 – 6 h
1	0.6	0.064	0.000	0.000	0.000
2	0.5	0.033	0.000	0.000	0.000
3	0.1	0.094 0.097	0.000 0.000	0.000 0.000	0.001 0.001
4	1.6	0.047	0.000	0.000	0.000
6	0.7	0.078 0.097	0.000 0.000	0.000 0.000	0.000 0.001

3.3.4 Discussion

While for the Hedwigepolder case the calibration resulted in a set of parameters that fitted both tests, here no single combination of parameter values is found that even fits two test periods. Van Hoven & Wopereis (2022) made a similar calibration for this test (yet with slightly different parameters) and found τ_c = 40 Pa & K_d = 35 cm^3/Ns, or, alternatively, for τ_c = 0 Pa a value of K_d = 15 cm^3/Ns. The values found here are around one order of magnitude higher.

Application of the values found by the EFA tests results in a very limited amount of erosion, namely several orders of magnitude less than observed, while for the Hedwigepolder, typically too large values were calculated, up to 7 times higher. This could be attributed to the changes that took place in the field over a period of more than 16 years, and to the fact that the wave overtopping tests were carried out in mildly wet conditions in late winter, while the samples were taken after several weeks of dry and sunny weather in late spring.

3.4 Wave overtopping tests at Lelystad (HWBP) - validation

In the course of 2024, the model can be validated using the results of the EFA tests on the boulder clay. The calculated erosion depth can be compared with the results from the laser scans of the surface before and after the wave overtopping test. From the data of the tests on the well compacted clay, a similar analysis as described in §3.2 can be carried out to calibrate for the erosion parameters. However, there are no results from tests to compare these with.

3.5 Estimation of the sensitivity of and uncertainties in the ISL model

For this activity, only a start was made. Further analysis needs to be done in 2024.

3.6 Influence of including the clay cover on the probability of failure

At present, safety assessments for dikes regarding the probability of failure from wave overtopping and its impact on the landside slope in the Netherlands generally consider grass erosion only, employing the Cumulative Overload Method (COM). This approach may be extended by considering the clay layer underneath the grass layer including the upper part of the clay cover.

In the experiments described here, approximately the upper 20 cm was removed completely from a part of the slope to simulate the loss of the grass, in other words: failing the COM criterion. Of course, reality will be different, with failure of the COM criterion physically expressed by the loss of part of the grass cover and a hole of no strictly defined depth in the clay cover only – most of the grass cover will still be present, albeit damaged to some extent. It is likely, yet not certain, that the removal of the entire 20 cm results in a rather pessimistic situation. In other words, reality may generally (but not necessarily always) be less vulnerable to further damage.

After the remaining part of the clay cover has eroded down to the sandy core of the dike, (further) headcut erosion, followed by simultaneous deepening and widening of the breach will take place. From physical considerations and field observations, it is assumed that the duration of these later phases is relatively short.

For a typical situation, e.g. the test site near Lelystad, probabilistic simulations for design conditions can be made including three phases:
- Loading and erosion of the grass cover, based on the COM.
- Subsequently, loading and erosion of the well compacted clay layer (with erosion parameters calibrated employing the results of the photogrammetry analysis).
- Finally, loading and erosion of the boulder clay layer underneath (with erosion properties taken from the EFA tests).

For each simulation, for each of these phases the time to reach the end of the phase can be recorded (if reached), resulting in a probability of failure depending on the number of phases considered, i.e. also the influence of including the clay cover layer on the probability of failure.

For these simulations, either the approximation of the hydraulic boundary conditions as included in the preprocessing part of the $\text{OTE2C}_{\text{ISL}}$ model may be used, or the erosion model may be coupled to the Dutch HydraRing model enabling probabilistic calculations for all main dikes in the Netherlands. In 2023, already a start was made with this coupling, yet without concrete results.

3.7 Modelling of erosion, a remark

The results from the five tests at the Hedwigepolder indicate that for the volumetric erosion of clay (with grass roots), the governing parameter seems to be the overtopping water volume (cf. Figure 3.7). If that is indeed a better parameter to describe the erosion of this clay cover (to be confirmed first from the analysis of the Delfzijl and Lelystad cases), then a somewhat different approach might be followed.

Yet, this gives rise to (at least) the following questions:
- How to determine the erosion rate, other than from large scale wave overtopping simulations?
- Is there a relation between the average erosion depth which comes initially from the volumetric approach, and the maximum erosion depth usually focused on in experiments?

4 Conclusions and recommendations

4.1 Conclusions

As mentioned in the introduction, the final aim of the research is to:

> *“Develop a relation for the erosion of the landside slope by wave overtopping for various types of soil in a form that can be incorporated in the Dutch instruments applied for the safety assessment and design of the primary flood defences (known by the Dutch acronym “BOI)”.*

This report is intended as an intermediate report and only holds intermediate conclusions concerning the performance of a clay erosion model in combination with small scale laboratory tests to obtain the erosion parameters.

The combination of model and laboratory tests for parameters was validated with large scale wave overtopping tests at two locations. From this validation it can be concluded that the combination of model and laboratory tests is by far insufficient for prediction purposes in BOI.

The laboratory tests for the Hedwigepolder generally lead to a significant overestimation of the required parameter values to postdict the observed erosion. For the Delfzijl case, the laboratory tests (performed on samples taken more than sixteen years after the test, and in a different season), the opposite is true. Currently there is no conclusion possible what the cause of the large differences. This could either be the model itself or the loading part of the model or the difference between lab parameters and bulk parameters needed in the model. Or a combination of these factors.

4.2 Recommendations

Although erosion prediction of clay in wave overtopping conditions has proven to be difficult, large-scale experiments as presented in this report did prove a significant strength, supporting further research efforts. The same conclusion is given by Van Hoven & Wopereis (2022). In this report it was concluded that the clay core of a dike offers more resilience to wave overtopping than a grass covers including objects and transitions. Smale & Plenker (2022) support the claim of a significant impact on the probability of dike failure by including clay cover strength, by investigating the impact of a somewhat shorter or longer loading period. Further support justifying research efforts comes from the experiences during the storm surge of 1953, where the clay dikes along the polder of Krimpenerwaard were exposed to wave overtopping and overflow on a large scale. This caused extensive damage to the inner slope along a few kilometres of dike, however they did not fail. Only one limited breach occurred which was closed the next day, preventing severe flooding of the Krimpenerwaard (Rijkswaterstaat & KNMI, 1961).

Considering the final aim of the research, it is recommended to investigate whether a relation between cumulative wave overtopping volume and cumulative eroded soil volume, as found in all five tests at the Hedwigepolder, can also be found for the other tests on bare clay, at Delfzijl and Lelystad. If that is the case, it can be evaluated for its added value for safety assessments for Dutch dikes: does calculating beyond grass failure have a significant impact on the calculated probability of flooding? To this end, a modification of the approach adopted by Smale & Plenker (2022) seems worth to investigate.

The use of a relation between overtopping and eroded volume preferably be investigated first for a single case, e.g. near Lelystad. If successful, it should be investigated for several more cases, with a reasonable mutual variety, before it should enter the implementation phase towards BOI. These investigations may be done initially with the limited preprocessing possibilities in $\text{OTE2C}_{\text{ISL}}$, but ultimately needs to be carried out using HydraRing to ensure the model fits to the intended application environment.

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A Collaboration workplan

A.1 Collaboration on Erosion

This document outlines the collaboration on erosion between the following partners:

- Cerema/ESTP.
- ISL.
- UCLouvain.
- ESTP.
- Rijkswaterstaat.
- Deltares.

A.2 Scope of the project

Based on the objectives per partner the following aim was defined:

Aim: Predicting erosion due to wave overtopping of levees (partially) made out of clay with grass and determine a simple way to predict the erosion parameters of levees to serve as input for the numerical models.

A.3 Objectives per partner

ISL	Further develop the erosion modelling tool to allow a probabilistic assessment of the erosion speed of levees.
Cerema	Finish the work on the numerical modelling of wave overtopping with CFD models and an erosion model based on the Exner Equation. Also interested in integrating knowledge on cracks and soil on overtopping. This is a point we could investigate. With Cyrille: Find correlation between geophysical data and geotechnics. Continue to work on the correlation.
ESTP	Similar to the objectives of Cerema as ESTP and Cerema like to mount a partnership. Interested in looking into the impact of heterogeneity on the erosion process. Also interested in developing a new erodimeter based on the EFA and JET by separating the components of the EFA. This erodimeter should be applicable on larger samples of different dimensions and different loading directions like the direction angular to the soil.
Rijkswaterstaat	The objective of Rijkswaterstaat is a) to develop a validated erosion relation for clay subjected to wave overtopping which can be implemented in a simple fast numerical levee erosion model, and b) To develop a simple method to extend de results of the overtopping erosion relation to other levees.
Deltares:	develop a validated erosion model applicable to the Dutch context
UCLouvain	"Processing of the results (bare clay and lime-treated clay) to provide topography maps at selected time instants (precise how much?) and transmission of the well-formatted results to the partners. Coordination for the writing of a journal paper on the results, including numerical simulations and comparisons with measurements and find a way to translate the results to other levees."

A.4 Responsibilities per partner

- UCLouvain: Will be in charge of editing and combining the research into a report that can be transferred into a journal paper. In exchange Masoumeh will be first author on this paper. Myron mentions that in this paper need to mention how the research was funded.

For Cerema the funding information is not important to mention. However, it is important to publish a paper or report.

- Cerema: Perform model runs for the 3 different test cases.
- ISL + Deltares: Development of the simple numerical tool.
- ISL + Cerema: Comparison of the results based on the simple and complex erosion tools.
- ESTP + Deltares: test the sample from the levee in the Netherlands. Deltares can help in providing the samples. ESTP could test the samples, with a maximum of 4.
- Analysing results: UCL can aid in analysing the results from Chalk and clay.
- Validation: Deltares can aid in validation of the numerical model against 3 test cases:
  - Case 1: Polder2C's experiments.
  - Case 2: Large scale erosion experiment Delfzijl.
  - Case 3: Chalk and clay. The question here is whether the model also predicts that no erosion occurs.

A.5 Funding per partner

- Abdelkrim would like funding for his activities. A limited amount of work could be contributed in kind. Myron and André will inform Ludolph on the interest of ESTP to join BONSAI.
- ISL: Moez will need to discuss how much ISL can contribute. For a few days ISL can cover the costs. However, if the amount of work becomes too much additional external funding is required.
- Deltares is as partner of Rijkswaterstaat funded by Rijkswaterstaat.
- Cerema and Rijkswaterstaat are able to cover their own costs.
- UCLouvain: Time investments are covered. Would be nice if they could get a role in BONSAI.

A.6 Planning per partner

- Cerema:
  - Hydrodynamic modelling of overtopping using CFD: Almost done for Polder2C's test.
  - In September they could run the erosion model and CFD model for the Delfzijl case.
  - Erosion: To be started. Final results on erosion modelling from Polder2C's: start July.
  - In September: Run the model for Test 2 (Delfzijl).
  - Third test: Chalk and clay.
- ISL:
  - Compare tool Cerema and ISL: June.
  - Finishing first version of tool: June.
  - Probabilistic calculation with Deltares (August).
- Deltares:
  - Probabilistic calculation with ISL: (August).
  - Validation of the tool (1st run finished by end of September).
  - Sampling of clay in Delfzijl. Do this ASAP. (June).
  - Validation of model based on Delfzijl case: September.
  - Validation of third test (Chalk and Clay).
- ESTP:
  - Analysing the sample from Delfzijl:
  - One test per day. Depends on the number of samples 4 or 5 samples.
  - Testing could be early June.
  - Results by the end of summer.
- UCLouvain:
  - Provide the bathymetry from the Chalk and clay: May.
  - Concept report done in November.
  - Report done in December.

B Minutes of progress meetings

B.1 Theme erosion meeting 19 April 2023

The first meeting was held on 19 April 2023. The ‘minutes’ of this meeting is the workplan, included in Annex A of this report.

B.2 Theme erosion meeting 19 June 2023

This meeting was cancelled on short notice by Myron van Damme, because of other, more urgent, priorities.

B.3 Minutes Theme erosion meeting 18 September 2023

Present: Abdelkrim Bennabi, Claire Damblans, Philippe Sergent, Moez Jellouli, Masoumeh Ebrahimi & André Koelewijn, unable to attend: Myron van Damme

1. Opening

Because of connection issues by Philippe, no formal opening took place, the meeting really started about 20 minutes late.

2. Status of action points work plan

From the work plan ***with current status**:*

- Cerema:
  - Hydrodynamic modelling of overtopping using CFD: Almost done for Polder2C’s test ***done.***
  - In September they could run the erosion model and CFD model for the Delfzijl case. ***yet to be done.***
  - Erosion: To be started. Final results on erosion modelling from Polder2C’s: start July ***no status known.***
  - In September: Run the model for Test 2 (Delfzijl) ***yet to be done***.
  - Third test: Chalk and clay. ***yet to be done.***
- ISL:
  - Compare tool Cerema and ISL: June. ***not yet discussed with Cerema.***
  - Finishing first version of tool: June ***done.***
  - Probabilistic calculation with Deltares (August) ***yet to be done.***
- Deltares:
  - Probabilistic calculation with ISL: (August) ***yet to be done.***
  - Validation of the tool (1st run finished by end of September) ***yet to be done.***
  - Sampling of clay in Delfzijl. Do this ASAP. (June) ***done.***
  - Validation of model based on Delfzijl case: September ***yet to be done.***
  - Validation of third test (Chalk and Clay). ***yet to be done.***
- ESTP:
  - Analysing the sample from Delfzijl: ***done.***
  - One test per day. Depends on the number of samples 4 or 5 samples ***done.***
  - Testing could be early June. ***Done.***
  - Results by the end of summer ***yet to be reported.***
- UCLouvain:
  - Provide the bathymetry from the Chalk and clay: May ***done.***
  - Concept report done in November. ***yet to be done.***
  - Report done in December. ***yet to be done.***

5. Update by Phillippe on Simulating overtopping erosion

Philippe tells about uncertainties regarding the boundary conditions and erosion parameters. Grass is assumed to be present everywhere, it is not excavated. Yet 15 times more erosion is calculated using the erosion parameters given, than observed in the field.

André suggests that the presence of the grass roots on top (ever more as erosion progresses) effectively reduced the shear stresses exerted on the clay. With less effective load, the erosion is also less.

A factor of 10 reduction of the E_0 parameter in Table 2 is suggested by Masoumeh to achieve a better match with the field observations. The influence of the grass roots may contribute to this, yet she thinks it was mostly a matter of local scour.
Abdelkrim puts in that the various EFA tests varied with a factor of 3 to 30, to put the factor 15 more in context.

One calculation is made, for test BC2_1 (irregular waves), assuming 300 litres/meter, and the result is multiplied by the number of waves. Philippe asks to provide more data on the boundary conditions as observed/measured; → Masoumeh will provide these details.
Moez: A peculiar element is the equal velocity from P2 until P10. And the mixture of air and water is questioned.

The amount of erosion is also considered more than the 10 cm mentioned.
→ Masoumeh will share a recently submitted journal manuscript.

3. Update by Moez on the status of the erosion tool

Moez presents the user interface of the most recent version, probably the final version, of the ISL tool, including modified Monte Carlo simulation.
The erodibility distribution he shows is assumed to be Gaussian lognormal distributed.

4. Update by Abdelkrim/Claire on determining the soil erodibility

→ Abdelkrim will send the results around right after the meeting, also the presentation that was shown.
One tube was damaged, therefore only five of the six sample could be tested.
Influence of swelling at low velocities; this phenomenon doesn't occur often, typically, but here it occurred at every sample. The influence on the results is not completely clear. It does stimulate the erosion rate at low flow velocities. The saturation step takes 1 hour. The complications arising from swelling samples in combination with the test set-up are discussed.

6. Next meeting

Tue Nov 7, 10:00-11:30, online with MS Teams.

B.4 Minutes Theme erosion meeting 7 November 2023

1. **Opening**
2. **Status of action points work plan**

From the work plan

- Cerema:
  - Hydrodynamic modelling of overtopping using CFD: *Almost done for Polder2C's test. Simulated the results for new boundary conditions which were discussed with Masoumeh. This gives peak front velocities of 7m/s instead of 11m/s.*
  - In September they could run the erosion model and CFD model for the Delfzijl case. *Phillippe will have a look at the Delfzijl case and have a look at it in the following weeks.*
  - Erosion: To be started. Final results on erosion modelling from Polder2C's: start July *This will start soon using the new front velocities. It is expected that the results will be much better. Results expected by the 21st of November.*
  - In September: Run the model for Test 2 (Delfzijl) *Phillippe will have a look at the Delfzijl case and have a look at it in the following weeks.*
  - Third test: Chalk and clay. *Cerema will look at this for the hydrodynamics. A check will be made between the measured and critical shear stress.* ***Myron*** *will send a copy of the report to everyone.* ***Masoumeh*** *will send the steering files.*
- ISL:
  - Compare tool Cerema and ISL: June. ***Phillippe*** *will contact ISL.*
  - Finishing first version of tool: June ***done.***

  - Probabilistic calculation with Deltares (August) ***Moez** will work with André to provide a python script that can be run.*
- Deltares:
  - Probabilistic calculation with ISL: (August) *André got stuck because he got an error message when starting the ISL model due to the Python version. André contacted Moez about this and will keep in touch with Moez on this.*
  - Validation of the tool (1st run finished by end of September) *(See action 1)*
  - Sampling of clay in Delfzijl. Do this ASAP. (June) ***done.***
  - Validation of model based on Delfzijl case: September (*Required model run).*
  - Validation of third test (Chalk and Clay). *(Requires the model and the report).*
- ESTP:
  - Analysing the sample from Delfzijl: ***done.***
  - One test per day. Depends on the number of samples 4 or 5 samples ***done.***
  - Testing could be early June. ***Done.***
  - Report has been sent.

3. **Analysis data**
   - Comparison measured erodibility against predicted erodibility from large scale tests. *The derived erodibility has not been established yet due to problems with running the model.*
   - Additional data collection. *If we provide Phillippe with the Bathymetry and provide them with the released volumes he can run the model for it. **Myron** can share the initial and final bathymetry with Philippe after checking with Bianca. **Myron** will check with Bianca.*

   Analysis in 2024
4. **Reporting of the findings (Masoumeh).** Masoumeh will schedule a meeting with Myron and André to Masoumeh to schedule a discussion on the table of contents. Masoumeh has not time until 4th of December. After that she can start writing. Final report half of 2024.
5. **New meeting: 18-01-2024 9:30-11:00**

C OTE2C$_{\text{ISL}}$ code

C.1 Overview

This annex contains the python code of the OverTopping Erosion module as prepared for the Interreg 2Seas-project Polder2C’s by ISL Ingénierie in Lille, France.

The deterministic model is provided with a graphical user interface, but it can be run in batch mode from the command line as well. It is started by `call_batch2`, as given in §C.2. This calls `OTE2C`, as given in §C.3, which in turn imports `Boudary_Condition` (as given in §C.4), `Grass` (as given in §C.5), `Discharge` (as given in §C.6) and `Erosion` (as given in §C.7), while `call_batch2` further gets general data on the period calculated, the dike geometry, the sea conditions, the grass and the soil properties from `call2`, as given in §C.8.

The probabilistic shell, employing the same routines, is given in §C.9.

C.2 call_batch2.py

```
import subprocess
import pkg_resources
import sys

# Check if a module is installed in Python and, if not, install it
for package in ['numpy','matplotlib']:
    try:
        dist = pkg_resources.get_distribution(package)
    except pkg_resources.DistributionNotFound:
        print('{} installation...'.format(package))
        subprocess.check_call([python, '-m', 'pip', 'install',
package])

sys.path.insert(1,'\\\\isllille\\Affaires\\20F017_Polder2Cs\\4_TECHN
IQUE\\Outil\\Sources\\Exemples\\Exemple10')

import numpy as np
import math
import OTE2C as OTE2C
import matplotlib.pyplot as plt
import ctypes

from call2 import *

def h(t) :
    return math.cos((t-
HightideTime)*2*3.1416/12.25/3600)*(HightideWaterLevel-
MeanSeaWaterLevel) \
           + MeanSeaWaterLevel

h2=np.vectorize(h)

#Input data reservoir
size=round((end_time-start_time)/time_step)
BCs = []
```

```
BCs.append(h2(np.linspace(0,end_time,size)))
BCs.append(np.linspace(0,end_time,size))    # Time series of water
level in reservoir
BCs.append(np.zeros(size)+hcrest-hdike)      # downstream water
level
BCs.append(np.linspace(0,end_time,size))    # Time series of
downstream water level
BCs.append(np.array([SignifiantWaveHeight ,Waveperiod ]));   # wave
definition height and période
BCs.append(IrregularWaves);                  # wave definition
height and période


#Input data dike
Geom=[]
Geom.append(hdike)     # initial crest height in m
Geom.append(hcrest)    # Crest level(m AD) Level of the dike crest
Geom.append(wcrest)    # Crest width
Geom.append(OSlope)    # Outwards slope 1:....
Geom.append(LSlope)    # Landside slope 1:....
Geom.append(Lcrest)    #Crest length

#Input data soil properties
soil=[]
soil.append(Mannings_coeff)  # Mannings coefficient in s/m^3
soil.append(shear_stress)    # critical shear stress in N/m2
soil.append(Erodibility)     # Erodibility [cm3/Ns]
soil.append(grassQlt)        #Grass quality, 7000 = Good, 4000 =
normal, 2000 =poor Grass, 0 = no grass.
soil.append(alpha_m)         #correction factor for transitions
soil.append(alpha_s)         #correction factor for critical
velocity
soil.append(Critvel)         #Critical velocity m/s

#Run settings
run=[]
run.append(weir_coeff)      # this is the weir coefficient with a
value between 0.7 and 1.4
run.append(coeff_2)         # coefficient which only works after the
crest has eroded away to the moment the breach reaches its full
depth for HZ contraction
run.append(coeff_3)         # coefficient which only will be applied
when the crest level is 0. fot HZ contraction
run.append(breach_factor)   # Proportionality factor between the
rate of breach widening and lowering
run.append(start_time)      # Start time of model runs
run.append(end_time)        # End time model runs
run.append(time_step)       # Time step model runs

#Model constants
Constants = []
Constants.append(9.81)  # Gravitational constant in m/s^2
Constants.append(1000)  # Density of water in kg/m^3
```

```
Output,X_Ero,Y_Ero,Dike_w = OTE2C.OTE2C(BCs,Geom,soil,run,
Constants,size)

TitlesOutput = ['Sea water level [m]', 'Mean discharge
[m3/s/ml]','Peak discharge [m3/s/ml]', 'Dike top level [m]',
                'Crest Width [m]','Freeboard [m]','Grass quality
[m²/s²]','Shear Stress [Pa]','E Depth [m]','Condition [-
]','Qpeak/Qmean [-]',
                'Impact speed [m/s]','X impact [m]','Y impact [m]']

#Initialize the window
user32 = ctypes.windll.user32
screensize = user32.GetSystemMetrics(0), user32.GetSystemMetrics(1)
W=13
H=11
fig=plt.figure(figsize=(W,H), dpi=80)
size = W*80 , H*80 + 70
x = screensize[0]//2 - size[0]//2
y = screensize[1]//2 - size[1]//2
thismanager = plt.get_current_fig_manager()
if hasattr(thismanager.window,'wm_geometry') :
    thismanager.window.wm_geometry("+%d+%d" % (x, y))
if hasattr(thismanager.window,'resize') :
    thismanager.window.resize(x, y)
fig.canvas.manager.set_window_title("OTE2C x="+str(x)+" y="+str(y))
major_ticks = np.arange(start_time/3600, (end_time+1)/3600,
round((end_time-start_time)/4/3600)/2)

#Curve
def Draw_Curve(axis,col,label_Y):
    axis.plot(Output[:,0], Output[:,col])        #Draw curve
    axis.set(xlabel='time [hr]', ylabel=label_Y) #set axes labels
    axis.grid()                                  #Draw grid
    axis.set_xlim(start_time/3600,end_time/3600);#set x-axis limits
    axis.set_xticks(major_ticks)                 #set x-axis limits

axs = fig.subplots(4, 3)                         #set curves layout
Draw_Curve(axs[0,0],1,TitlesOutput[0])
Draw_Curve(axs[0,1],2,TitlesOutput[1])
Draw_Curve(axs[0,2],3,TitlesOutput[2])
Draw_Curve(axs[1,0],4,TitlesOutput[3])
Draw_Curve(axs[1,1],5,TitlesOutput[4])
Draw_Curve(axs[1,2],6,TitlesOutput[5])
Draw_Curve(axs[2,0],7,TitlesOutput[6])
Draw_Curve(axs[2,1],8,TitlesOutput[7])
Draw_Curve(axs[2,2],9,TitlesOutput[8])
Draw_Curve(axs[3,0],10,TitlesOutput[9])
Draw_Curve(axs[3,1],11,TitlesOutput[10])
Draw_Curve(axs[3,2],12,TitlesOutput[11])


plt.tight_layout()
plt.show(block=True)
```

C.3 OTE2C.py

```
import math
import numpy as np

import Boundary_Condition
import Grass
import Discharge
import Erosion

def OTE2C(BCs,Geom,soil,run, Constants,size):
    #Input data reservoir
    SWL  = BCs[0][BCs[0]>=-50]     # Sea Water Level
    Twlup = BCs[1][BCs[1]>=0]       # Time series of water level in
reservoir
    DSwl = BCs[2][BCs[2]>=0]        # downstream water level
    Twlca = BCs[3][BCs[3]>=0]       # Time series of downstream
water level
    SignifiantWaveHeight =BCs[4][0] # Wave height
    Waveperiod =BCs[4][1]           # Wave period
    IrregularWaves = BCs[5]         # Irregular waves

    #embankment geometry Main embankment
    hdike=Geom[1-1]                  # dike height in m (land side)
    hcrest=Geom[2-1]                 # Crest level(m AD) Level of
the dike crest
    Cw = Geom[3-1]                   # Crest width
    OSlope = Geom[4-1]               # Outwards slope 1:....
    Slope = Geom[5-1]                # Landside slope 1:....
    Lcrest = Geom[6-1]               # Crest length

    #Input data soil properties [Not all parameters are used for the
headcut mode
    n = soil[1-1]                    # mannings coefficient in
s/m^[1/3-1]
    tau_c = soil[2-1]                # critical shear stress in N/m2
    kd = soil[3-1]                   # Erodibility

    # Grass
    grass_cum = soil[4-1]            # grass cumulative overload
method
    alpha_m = soil[5-1]              # correction factor for
transitions
    alpha_a = (1+4/(Slope**2))**0.5  # acceleration coefficient
    alpha_s = soil[6-1]              # correction factor for
critical velocity
    CritVel = soil[7-1]              # Critical velocity m/s

    #Model constants
    g = Constants[1-1]               # Gravitational constant
    rho = Constants[2-1]             # Density of water

    #Run settings
    coeff= run[1-1]                  # this is the weir coefficient
with a value between 0.7 and 1.4
```

```
    coeff2 = run[2-1]                # coefficient which only works
after the crest has eroded away to the moment the breach reaches its
full depth for HZ contraction
    coeff3 = run[3-1]                # coefficient which only will
be applied when the crest level is 0. for HZ contraction process-
based calculation requires an additional subroutine
    breach_factor = run[4-1]         # Proportionality factor
between the rate of breach widening and lowering
    Tstart = run[5-1]                # Start time of model runs
    Tend = run[6-1]                  # End time model runs
    Delta_t = run[7-1]               # Time steps model runs

    #Run settings
    Edepth=0                         # erosion depth for the headcut
calculation. Keep as 0.

    #Initialization of matrices
    Discharg = np.zeros((size,2))
    BreachDepth = np.zeros((size,2))
    BreachWidth = np.zeros((size,2))
    BreadthAveDis = np.zeros((size,2))
    Condition = 0

    #initialisation Output
    MwOut = np.zeros((size,8))
    Nb_Output = 15
    Output = np.zeros((size,Nb_Output))
    Dike_w = []

    #initialisation impact
    X_Ero=0;
    Y_Ero=0;
    B_Impact=0;
    Dw=Cw;

    #-----------------------------------------------------------------
--#
    #     Determine KD
#
    #-----------------------------------------------------------------
--#

    count=0;                                # counter: do not change
    kd=kd/1e6;                              # this transfers the Kd
value from cm3/Ns to m3/Ns
    HeadC=0.5*kd*1e6/1.76819/3600;          # Determines the headcut
coefficient from Kd based on the HR Breach approximation
    Hi = SWL[1];                            # Initial water level
    ng=0.02;                                # Manning coefficient
for grass (for flat grass on slopes > 1/10 cite TN71)
    hcr=hcrest;                             # Set initial invert
level
    minhcr=hcrest-hdike;                    # minimal value of hcr
    grad = 1/Slope;                         # Landside slope
gradient
```

```
    alpha = math.degrees(math.atan(grad));  # Landside slope angle
    Qtot=0;                                  # Initialization total
discharge
    VolumeIn=0;
    failure = 0;
    Decision=0;
    SeaLevel=0;
    wlca=DSwl[0];
    tau=0;
    Hs_coef=1;

    #---------------------------------------------------------------
--#
    #       RUN OTE2C
#
    #---------------------------------------------------------------
--#

    if IrregularWaves : print("Irregular waves")
    for ii in range(size):
        Time=ii*Delta_t;
        Time2=Time/3600;

        # Upstream and dowstream conditions
        SeaLevel=max(Boundary_Condition.UpStream(Time,Twlup,SWL),
hcrest-hdike+0.001);
        wlca=Boundary_Condition.DownStream(Time,Twlca,DSwl);

        # Irregular waves : we apply a coefficient for 5 different
levels of wave heights corresponding to Rayleigh distribution
        # Hypothesis = Signficiant wave height = 30% exceedance in
Rayleigh distribution
        if IrregularWaves:
            if ii%5 == 0:
                Hs_coef = 0.293
            elif ii%5 == 1:
                Hs_coef = 0.751
            elif ii%5 == 2:
                Hs_coef = 1.429
            elif ii%5 == 3:
                Hs_coef = 0.990
            elif ii%5 == 4:
                Hs_coef = 0.539

        # Wave overtopping flows
        Hs=min(SignifiantWaveHeight*Hs_coef,(SeaLevel-(hcrest-
hdike))*2/3);
        Tfranc,qcar,Qpic,Qbase=Discharge.Waveflow(Waveperiod, Hs,
hcr-SeaLevel, g, OSlope)
        Umax = Discharge.Step2_U(Qpic)
        x, y, Beta, Vimpact=Discharge.Step3_impact(Umax, Slope, g)

        if (grass_cum > 0):
            # Grass erosion, if any
```

```
            grass_cum = max(0, grass_cum -
Grass.CumOvldMeth(alpha_m,alpha_a,alpha_s,Umax,CritVel,(Delta_t/Wave
period)))
        else :
            #Headcut erosion

Edepth,Dw,hcr,Condition,tau=Erosion.Headcut(Condition,Delta_t,Qpic,E
depth,Lcrest,Slope,OSlope,Tfranc/Waveperiod,g,SeaLevel,wlca,hcr,hcre
st,minhcr,rho,kd,tau_c,n,alpha,Dw,HeadC,breach_factor,X_Ero,Y_Ero)

        if (Edepth>0) and (B_Impact==0):
            #Impact + start erosion
            X_Ero=x;
            Y_Ero=y;
            Dw=Cw+X_Ero;
            B_Impact=1;
        if(Dw<Cw):
            #Start crest erosion
            Cw=Dw;


Output[ii]=EndOfTimeStep(Nb_Output,Time,SeaLevel,hcr,qcar,Qpic,Cw,hc
r-
SeaLevel,grass_cum,tau,Edepth,Condition,Waveperiod/Tfranc,alpha_a*Um
ax,x,y,Dw)
        Dike_w.append(Dw)

    return Output,X_Ero,Y_Ero,Dike_w;



def
EndOfTimeStep(Nb_Output,Time,SeaLevel,hcr,qcar,Qpic,Cw,Freebd,grass_
cum,tau,Edepth,Condition,Qratio,Vimpact,x,y,Dw):
#for plotting purposes
    Output=np.zeros(Nb_Output);
    Output[0]=Time/3600;
    Output[1]=SeaLevel;
    Output[2]=qcar;
    Output[3]=Qpic;
    Output[4]=hcr;
    Output[5]=Cw;
    Output[6]=Freebd;
    Output[7]=grass_cum;
    Output[8]=tau;
    Output[9]=Edepth;
    Output[10]=Condition;
    Output[11]=Qratio;
    Output[12]=Vimpact;
    Output[13]=x;
    Output[14]=y;
    return Output;
```

C.4 Boundary_Condition.py

```
import math
import numpy as np
```

```
def UpStream(Time,Twlr,USbc):
#Twlr = Time series of water level in reservoir
#USbc = water level reservoir in m
    if(Time>min(Twlr)):
        lower = np.sum(np.heaviside(Time - Twlr,0.5)==1) -1;
        a = np.linspace(1,len(Twlr),len(Twlr));
        B = a*(np.heaviside(Twlr-Time,0.5)>0.49);
        upper = math.trunc(min([j for j in B if j > 0])) -1;
        if upper==lower:
            wlr = USbc[lower];
        else:
            wlr = USbc[lower]+(USbc[upper]-
USbc[lower])/(Twlr[upper]-Twlr[lower])*(Time-Twlr[lower]);
    else:
        wlr = USbc[0];
    return wlr;

def DownStream(Time,Twlca,DSwl):
#Twlca = Time series of downstream water level
#DSwl = downstream water level
    if(Time>min(Twlca)):
        lower = sum(np.heaviside(Time - Twlca,0.5)==1)-1;
        a = np.linspace(1,len(Twlca),len(Twlca));
        B = a*(np.heaviside(Twlca-Time,0.5)>0.49);
        upper = math.trunc(min([j for j in B if j > 0]))-1;
        if upper==lower:
            wlca = DSwl[lower];#Fwlr
        else:
            wlca = DSwl[lower]+(DSwl[upper]-
DSwl[lower])/(Twlca[upper]-Twlca[lower])*(Time-Twlca[lower]);
    else:
        wlca = DSwl[0];
    return wlca;
```

C.5 Grass.py

```
import math
import numpy as np
import Erosion

def CumOvldMeth(alpha_m,alpha_a,alpha_s,Velocity,critVel,N_waves):
#Damage = cumulated damage
#alpha_m = correction factor for transitions
#alpha_a = acceleration factor at impact = (1 + 4.tg²(slope angle))
#alpha_s = correction factor for critical velocity
#Velocity = mean velocity at crest
#critVel = critical velocity
#N_waves = number of waves for delta_T
    f_erosion = alpha_m*(alpha_a*Velocity)**2
    f_crit = alpha_s*critVel**2
    if f_erosion == 0 :
         coef0 = 0
    else :
         coef0 = Erosion.coef_corr((f_crit/f_erosion)**0.5,2)
```

```
    return N_waves * max(0,coef0*(alpha_m*(alpha_a*Velocity)**2 -
alpha_s*critVel**2))
```

C.6 Discharge.py

```
import math
import numpy as np
import csv
import call2 as call2
import OTE2C as OTE2C

def Waveflow(T, Hm0, R, g, Slope):
    # T : vawe period (s)
    # Hm0 : wave height m
    # R freeboard m
    # g gravity
    # SLOPE : pente du talus amont (H/V) (à traduire)
    # warning not flow but flow per width

    Tm0=T/1.1
    tanalpha=1/Slope
    alpha = math.atan(tanalpha)
    Lm0= g*Tm0*Tm0/2/math.pi
    Sm0=Hm0/Lm0
    Em=tanalpha/math.sqrt(Sm0)
    if R<0:
        Qbase=math.sqrt(2*g)*(-2/3*R)*math.sqrt(-R/3)
        Rap=0
    else:
        Qbase=0
        Rap=R/Hm0

    #---------------------------------------------------------------
--------------------------------#
    #                              Formule de franchissement
#
    #---------------------------------------------------------------
--------------------------------#
    if Em>=7:
        qcar=math.sqrt(g*pow(Hm0,3))*0.16*math.exp(-(
Rap/(0.33+0.022*Em)))
        # base formula (5.15 eurotop 2018)
    else:

qcar1=math.sqrt(g*pow(Hm0,3))*0.023/math.sqrt(tanalpha)*Em*math.exp(
-pow(2.7*Rap/Em,1.3))
        # base formula (5.10 eurotop 2018)
        qcar2=math.sqrt(g*pow(Hm0,3))*0.09*math.exp(-
pow(1.5*Rap,1.3))
        # base formula (5.11 eurotop 2018)
        qcar=min(qcar1,qcar2)
    #---------------------------------------------------------------
--------------------------------#

#    K=0.5*math.exp(-math.pow(1.5*Rap/Em,1.3)) Triangular approx
```

```
    K=0.25*math.exp(-math.pow(1.5*Rap/Em,1.3)) # rectangular approx
27/09/2022
    Qmax=qcar/K
    Tfranc=K*T
#    Qpic=qcar*2*T/Tfranc # linéar variation of Q     Triangular
approx
    Qpic=qcar*T/Tfranc # linéar variation of Q     rectangular
approx
    return Tfranc,qcar+Qbase,Qpic+Qbase,Qbase

def Tcrit(T, Tfranc, Qbase, Qpic, Qcritique):
    if Qcritique>Qpic:
        t2=0
    else:
        if Qcritique<Qbase:
            t2=T
        else:
            t2=Tfranc*(Qcritique-Qpic)/(Qbase-Qpic)
    return t2

def dischargeT(T0,T,Tfranc, Qbase, Qpic):
# T0
# T wave crossing period
    if T>Tfranc:
        q=Qbase
    else:
        q=Qbase + (Qpic-Qbase)*(Tfranc-T)/Tfranc
    return q

def Step2_U(Q):
# Qmax m3/s/m
# : S.Hughes, 2012
    return 2.6*math.sqrt(Q)

def Step3_impact(U, Slope,g):
# Um m/s
# Slope pente du talus aval (H/V) (à traduire)
# g gravity
# résult
# x,y : position of the impact
# beta : incidence de l'impact
# Vimpact : vitesse à l'impact
    tanalpha = 1/Slope
    alpha = math.atan(tanalpha)
    x= 2*U**2/g*tanalpha
    y= 2*U**2/g*tanalpha**2
    Beta = - alpha + math.atan(2*tanalpha)
    Vimpact = U * math.sqrt(1+4*tanalpha**2)
    return x, y, Beta, Vimpact
```

C.7 Erosion.py

```
import math
import numpy as np
```

```
def
Headcut(Condition,Delta_t,Qpic,Edepth,Lcrest,Slope,OSlope,TfT0,g,wlu
p,wlca,
hcr,hcrest,minhcr,rho,kd,tau_c,n,alpha,Dw,HeadC,breach_factor,x,y):
# Qpic = peak discharge (rectangular approach)
# wlup = upstream water level
# wlca = downstream water level
# (hcr = invert level)
# hcrest = Crest height
# Lcrest = Crest length
# Slope = Landside slope
# OSlope = Outwards slope
# TfT0 = Qcar/Qpic ratio (rectangular approach)
# Edepth = erosion depth
# g = Gravitational constant
# rho = Density of water
# kd = Erodibility  (m3/Ns)
# tau_c = critical shear stress in N/m2
# n = mannings coefficient in s/m^[1/3-1]
# alpha = Landside slope angle
# Dw = Crest width + x impact;
# HeadC = Determines the headcut coefficient from Kd based on the HR
Breach approximation
# breach_factor = Proportionality factor between the rate of breach
widening and lowering
    tau=0
    if (Qpic>0.001):
        #Headcut Erosion
        ib=1/Slope;                                              #
Landside slope gradient
        de=((Qpic**2*n**2)/math.sin(math.radians(alpha)))**0.3;  #
Normal depth
        dc=(Qpic**2/g)**(1/3);                                   #
Critical depth
        if Edepth<dc:
            #before the code reaches the headcut stage
            if Condition>=0:
                # Determine bed shear stress
                tau=rho*g*de*math.sin(math.atan(1/Slope)); #this
calculated everything in rad.
                # Determine erosion rate with Erosion equation
                if tau-tau_c>=0:
                    E=kd*(tau-tau_c);
                else:
                    E=0;
                # Determine erosion depth
                if tau == 0 :
                    coef0 = 0
                else :
                    coef0 = coef_corr((tau_c/tau)**(1/0.6),0.6)
                Edepth=Edepth+E*Delta_t*TfT0*coef0;
                if Edepth>hcrest-minhcr-y:
                    Edepth=hcrest-minhcr-y;
        else:
            Condition=1;
```

```
            Dw=Dw-
HeadC*(Qpic*Edepth)**(1/3)*Delta_t*TfT0*coef_corr(0,1/3); #new value
crest width
            Er1=rho*g*dc*0.011*(Edepth/dc)**0.582;
            Er2=rho*g*de*(math.sin(math.atan(1/Slope)));
            tau=max(Er1,Er2);
            if tau == 0 :
                 coef0 = 0
            else :
                 coef0 = coef_corr((tau_c/tau)**(1/0.6),0.6)
            Edepth=Edepth+max(kd*(tau-tau_c)*Delta_t*TfT0*coef0,0);
            # Erosion below the foundation level of the levee is
prevented
            if Edepth>hcrest-minhcr-y:
                Edepth=hcrest-minhcr-y;
            # Erosion causes the landside slope headcut to retreat.
            # Erosion of the crest is not allowed unless it is due
to the retreat of the landside slope
            if (Dw<=0 and hcr>=0):
                E=1/Slope*HeadC*(Qpic*Edepth)**(1/3);
                hcr=hcr-
1/OSlope*HeadC*(Qpic*Edepth)**(1/3)*Delta_t*TfT0*coef_corr(0,1/3);
            if hcr<minhcr:
                hcr=minhcr;
            if Edepth>hcrest-minhcr-y:
                Edepth=hcrest-minhcr-y;

    return Edepth,Dw,hcr,Condition,tau


def criticaldischarge(rho,g,tau_c,Slope,n):
     h_critical=tau_c/rho/g/math.sin(math.atan(1/Slope))

Q_critical=math.sqrt(h_critical**(1/0.3)*math.sin(math.atan(1/Slope)
))/n
     return Q_critical

# Correction for rectangular approximation
def coef_corr(gamma, Npower):
# gamma = Threshold / Qcrest
# Npower = exponent of the law to be integrated
    if gamma < 0 or gamma >= 1 :
        return 0
    else :
        coef0 = 1 - (Npower+1)*gamma**Npower +
Npower*gamma**(Npower+1)
        coef0 = 2 * coef0 / (Npower+1) / (1-gamma**Npower)
        return coef0

def tau_a(Q,rho,g,Slope,n):
     de=((Q**2*n**2)/math.sin(math.atan(1/Slope)))**0.3;  # Normal
depth
     tau=rho*g*de*math.sin(math.atan(1/Slope));           #this
calculated everything in rad.
     return tau
```

```
def tau_b(Q,rho,g,Slope,n):
     de=((Q**2*n**2)/math.sin(math.atan(1/Slope)))**0.3;  # Normal
depth
     tau=rho*g*de*math.sin(math.atan(1/Slope));           #this
calculated everything in rad.
     return tau
```

C.8 call2.py

```
#General data
start_time = 0                #Start time(s) Start time of model
runs
end_time = 86400              #End time(s) End time model runs
time_step = 120               #Time step(s) Time steps model runs

#Dike geometry
hdike = 7.0                   #Dike height(m) Landside dike height
hcrest = 8.0                  #Crest level(m AD) Level of the dike
crest
wcrest = 3.0                  #Crest Width(m) Crest Width
Lcrest = 100.0                #Crest length(m) Crest length
OSlope = 2.5                  #Seaside slope(h/v) Seaside batter
(inclination from the vertical)
LSlope = 2.5                  #Landside slope(h/v) landside batter
(inclination from the vertical)

#Sea conditions
MeanSeaWaterLevel = 0.57      #Mean sea level(m AD) average sea
level between two tides
HightideWaterLevel = 4.71     #High tide Water level(m AD) Sea level
at high tide
HightideTime = 14200.0        #High tide Time(s) High tide time,
tide period is 43200 seconds (12 hours)
SignifiantWaveHeight = 1.43   #Signifiant wave height(m) Wave height
LowtideWaterLevel = -3.57     #Low tide sea level(m AD) Sea level at
low tide
Waveperiod = 10.0             #Wave period(s) Wave period
IrregularWaves = False        #Irregular Waves If true then Rayleigh
distribution of waves

#Grass
grassQlt = 2000.0             #Grass quality 7000 : good / 4000 :
normal / 2000 : poor grass / 0 : no grass
alpha_m = 1.0                 #Transition factor Correction factor
for transitions
alpha_s = 1.0                 #Velocity factor Correction factor for
critical velocity
Critvel = 4.0                 #Critical velocity(m/s) Critical
velocity

#Initial breach parameters
wbreach = 1.5                 #Breach width(m) initial breach width

#Soil properties
```

```
Mannings_coeff = 0.025        #mannings coefficient( s/m^(1/3))
Mannings_coeff
shear_stress = 20.0           #critical shear stress(N/m2) critical
shear stress
Erodibility = 10.0            #Erodibility(cm3/Ns) Erodibility

#Run settings
weir_coeff = 1.0              #Coefficient 1 weir coefficient on the
dike, value between 0.7 and 1.4
coeff_2 = 1.0                 #Coefficient 2 weir coefficient in the
breach
coeff_3 = 1.0                 #Coefficient 3 weir coefficient which
only works after the crest has eroded away to the moment the breach
reaches de dike height
breach_factor = 1.4           #Breach factor proportionality factor
between the rate of breach widening and lowering
```

C.9 call_proba2.py

```
# Copyright (c) [August 2023] [Moez JELLOULI - ISL, France]

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NonCommercial 4.0 International License.
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[jellouli@isl.fr].


import subprocess
import pkg_resources
import sys, os, webbrowser
import time

# Check if a module is installed in Python and, if not, install it
for package in ['numpy','matplotlib']:
    try:
        dist = pkg_resources.get_distribution(package)
    except pkg_resources.DistributionNotFound:
        print('{} installation...'.format(package))
        subprocess.check_call([python, '-m', 'pip', 'install',
package])

#
sys.path.insert(1,'\\\\isllille\\Affaires\\20F017_Polder2Cs\\4_TECHN
IQUE\\Outil\\Sources\\Exemples\\Exemple10')
sys.path.insert(1,os.path.dirname(os.path.abspath(__file__)))

import numpy as np
import pandas as pd
import math
import OTE2C as OTE2C
import matplotlib.pyplot as plt
import ctypes
```

```
from call2 import *
import plotly.graph_objects as pltly
from plotly.subplots import make_subplots
import base64

# ---------> Beginning
if len(sys.argv) < 2 :
    print("Please specify the number of Monte Carlo iterations as
first argument")
    exit()
if not(sys.argv[1].isdigit()) or int(sys.argv[1]) < 0:
    print("Monte Carlo number of iterations is not valid")
    exit()
start_clock = time.time()

def simple_config(Hs, HighTide, CritVel, CritShear, Erod):

    #Input data reservoir
    size=round((end_time-start_time)/time_step)
    timeserie = np.linspace(0,end_time,size)
    h2 = np.cos((timeserie-
HightideTime)*2*3.1416/12.25/3600)*(HighTide-MeanSeaWaterLevel) \
           + MeanSeaWaterLevel

    BCs = []
    BCs.append(h2)
    BCs.append(timeserie)     # Time series of water level in
reservoir
    BCs.append(np.zeros(size)+hcrest-hdike)      # downstream water
level
    BCs.append(timeserie)     # Time series of downstream water
level
    BCs.append(np.array([Hs ,Waveperiod ]));   # wave definition
height and période
    BCs.append(IrregularWaves);                  # wave definition
height and période


    #Input data dike
    Geom=[]
    Geom.append(hdike)     # initial crest height in m
    Geom.append(hcrest)    # Crest level(m AD) Level of the dike
crest
    Geom.append(wcrest)    # Crest width
    Geom.append(OSlope)    # Outwards slope 1:....
    Geom.append(LSlope)    # Landside slope 1:....
    Geom.append(Lcrest)    #Crest length

    #Input data soil properties
    soil=[]
    soil.append(Mannings_coeff)  # Mannings coefficient in s/m^3
    soil.append(CritShear)       # critical shear stress in N/m2
    soil.append(Erod)            # Erodibility [cm3/Ns]
    soil.append(grassQlt)        #Grass quality, 7000 = Good, 4000 =
normal, 2000 =poor Grass, 0 = no grass.
```

```
    soil.append(alpha_m)         #correction factor for transitions
    soil.append(alpha_s)         #correction factor for critical
velocity
    soil.append(CritVel)         #Critical velocity m/s

    #Run settings
    run=[]
    run.append(weir_coeff)      # this is the weir coefficient with
a value between 0.7 and 1.4
    run.append(coeff_2)         # coefficient which only works after
the crest has eroded away to the moment the breach reaches its full
depth for HZ contraction
    run.append(coeff_3)         # coefficient which only will be
applied when the crest level is 0. fot HZ contraction
    run.append(breach_factor)   # Proportionality factor between the
rate of breach widening and lowering
    run.append(start_time)      # Start time of model runs
    run.append(end_time)        # End time model runs
    run.append(time_step)       # Time step model runs

    #Model constants
    Constants = []
    Constants.append(9.81)  # Gravitational constant in m/s^2
    Constants.append(1000)  # Density of water in kg/m^3

    Output,X_Ero,Y_Ero,Dike_w = OTE2C.OTE2C(BCs,Geom,soil,run,
Constants,size)

        # Output[0]=Time/3600;
        # Output[1]=SeaLevel;
        # Output[2]=qcar;
        # Output[3]=Qpic;
        # Output[4]=hcr;
        # Output[5]=Cw;
        # Output[6]=Freebd;
        # Output[7]=grass_cum;
        # Output[8]=tau;
        # Output[9]=Edepth;
        # Output[10]=Condition;
        # Output[11]=Qratio;
        # Output[12]=Vimpact;
        # Output[13]=x;
        # Output[14]=y;
    return np.min(Output[:,4])-Output[0,4]

def load_cdf(file_name):
    new_cdf = np.loadtxt(file_name, delimiter=';',skiprows = 1)
    new_data = np.array([0.0,np.min(new_cdf[:,1])])
    new_cdf = np.concatenate(([new_data], new_cdf))
    max_cdf = new_cdf[-1,1]+(1-new_cdf[-1,0])/(new_cdf[-1,0]-
new_cdf[-2,0])* \
        (new_cdf[-1,1]-new_cdf[-2,1])
    new_data = np.array([1.0,max_cdf])
    new_cdf = np.concatenate((new_cdf, [new_data]))
    return new_cdf
```

```
def deform_cdf(cdf0,power,Resolution):
    cdf_grid = np.linspace(0,1,Resolution+1)
    cdf_grid = np.power(cdf_grid,power)
    cdf_grid = min(cdf0[:,1]) + cdf_grid * (max(cdf0[:,1]) -
min(cdf0[:,1]))
    grid2 = np.interp(cdf_grid, cdf0[:,1], cdf0[:,0])
    grid2 = grid2[1:] - grid2[:-1]
    cdf_grid = cdf_grid[1:]
    cdf_grid = np.concatenate((cdf_grid.reshape(-1,
1),grid2.reshape(-1, 1)),axis=1)
    return cdf_grid

def calc_point_size(vect) :
    v2 = np.log10(vect)
    return 12*np.maximum(16+v2.max()/2+v2,1/6)

def plot_scatter_map_2D(i, j, v1, v2, vsize, hover_text, x0label,
y0label, fig):
    scatterplot = pltly.Scatter(
        x=v1,
        y=v2,
        hovertext=hover_text,
        hoverinfo='text',
        mode='markers',
        marker=dict(size=vsize,color=vsize))
    fig.add_trace(scatterplot, row=i, col=j)
    fig.update_xaxes(title_text=x0label, range=[v1.min()-0.01,
v1.max()+0.01], row=i, col=j)
    fig.update_yaxes(title_text=y0label, range=[v2.min()-0.01,
v2.max()+0.01], row=i, col=j)

def plot_scatter_map_3D(i, j, v1, v2, v3, vsize, hover_text,
x0label, y0label, z0label, fig):
    scatterplot = pltly.Scatter3d(
        x=v1,
        y=v2,
        z=v3,
        hovertext=hover_text,
        hoverinfo='text',
        mode='markers',
        marker=dict(size=vsize,color=vsize))
    fig.add_trace(scatterplot, row=i, col=j)
    fig.update_scenes(patch=dict(
                xaxis_title=x0label,
                yaxis_title=y0label,
                zaxis_title=z0label,
                xaxis_range=[v1.min()-0.01, v1.max()+0.01],
                yaxis_range=[v2.min()-0.01, v2.max()+0.01],
                zaxis_range=[v3.min()-0.01, v3.max()+0.01]),
                row=i, col=j)

def make_first_plot():
    point_size = calc_point_size(failures['pdens']/total_density)
    hover_text = failures.apply(lambda x : round(x,2)).apply(
```

```
        lambda row: f'( SWH={row["SWH"]}, HT={row["HighTide"]}, 
CritS={row["CritS"]}, Erod={row["Erodability"]}, 
CritV={row["CritV"]} )',axis=1)

    fig = make_subplots(rows=1, cols=2,
                        subplot_titles = ('Sea conditions','Dike 
properties'),
                        specs=[[{'type': 'scatter'}, {'type': 
'scatter3d'}]])

    fig.update_layout(title={
            'text': "OTE2C - Probabilistic module",  # Texte du 
titre
            'x': 0.5,  # Position horizontale du titre (0-1)
            'y': 0.98,  # Position verticale du titre (0-1)
            'xanchor': 'center',  # Ancrage horizontal du titre 
('left', 'center', 'right')
            'yanchor': 'top',  # Ancrage vertical du titre ('top', 
'middle', 'bottom')
            'font': dict(size=36, family='Calibri')},  # Taille et 
police du titre
        annotations=[pltly.layout.Annotation(text="Failure 
probability = "+format(prob_fail)+" per 
year",x=0.5,y=1.04,ay='top')],
        showlegend=False)
    fig.update_layout(margin=dict(t=135,b=50,l=50,r=50))
    fig.update_layout(images=[dict(
        source='data:image/png;base64,{}'.format(logoISL.decode()),
        xref="paper", x=0.02,
        yref="paper", y=1.13,
        sizex=0.1, sizey=0.1,
        xanchor="left", yanchor="top"),
        dict(
        
source='data:image/png;base64,{}'.format(logoPolder.decode()),
        xref="paper", x=0.1,
        yref="paper", y=1.12,
        sizex=0.12, sizey=0.12,
        xanchor="left", yanchor="top"
        )])

    plot_scatter_map_2D(1, 1, failures['SWH'], failures['HighTide'], 
point_size, hover_text,
        'Signifiant Wave Height (m)',
        'High Tide WL (m)', fig)

    plot_scatter_map_3D(1, 2, failures['CritS'], 
failures['Erodability'], failures['CritV'], point_size, hover_text,
        'Critical Shear Stress (Pa)',
        'Erodability (cm3/N/s)',
        'Critical Velocity (m/s)', fig)

    # Sauvegarde du graphique en HTML
    fig.write_html('OTE2C_ScatterPlot.html')
    return fig
```

```
def update_scatter_map(fig):
    point_size = calc_point_size(failures['pdens']/total_density)
    hover_text = failures.apply(lambda x : round(x,2)).apply(
        lambda row: f'( SWH={row["SWH"]}, HT={row["HighTide"]},
CritS={row["CritS"]}, Erod={row["Erodability"]},
CritV={row["CritV"]} )',axis=1)
    # 2D map
    fig.update_traces(x=failures['SWH'], y=failures['HighTide'],
                      marker=dict(size=point_size,color=point_size),
                      hovertext=hover_text,
                      row=1, col=1)
    fig.update_xaxes(range=[failures['SWH'].min()-0.01,
failures['SWH'].max()+0.01], row=1, col=1)
    fig.update_yaxes(range=[failures['HighTide'].min()-0.01,
failures['HighTide'].max()+0.01], row=1, col=1)
    # 3D map

    fig.update_traces(x=failures['CritS'],
y=failures['Erodability'], z=failures['CritV'],
                      marker=dict(size=point_size,color=point_size),
                      hovertext=hover_text,
                      row=1, col=2)
    fig.update_scenes(patch=dict(
            xaxis_range=[failures['CritS'].min()-0.01,
failures['CritS'].max()+0.01],
            yaxis_range=[failures['Erodability'].min()-0.01,
failures['Erodability'].max()+0.01],
            zaxis_range=[failures['CritV'].min()-0.01,
failures['CritV'].max()+0.01]),
            row=1, col=2)
    fig.update_annotations(text="Failure probability =
"+format(prob_fail)+" per year")
    fig.write_html('OTE2C_ScatterPlot.html')

def make_discrt(vecteur,resolution):
    vmin = vecteur.min()
    Larg = (vecteur.max() - vmin)*1.001
    grid = vmin + (round((vecteur-vmin)*resolution/Larg-
0.5)+0.5)*Larg/resolution
    return grid

def plot_histograms(fail_df):
    df2 = fail_df.copy()   # We work on a copy
    total_density = fail_df['pdens'].sum()
    pd.options.mode.chained_assignment = None
    df2['SWH'] = make_discrt(df2['SWH'],20)
    df2['HighTide'] = make_discrt(df2['HighTide'],20)
    df2['CritV'] = make_discrt(df2['CritV'],20)
    df2['Erodability'] = make_discrt(df2['Erodability'],20)
    df2['CritS'] = make_discrt(df2['CritS'],20)
    pd.options.mode.chained_assignment = 'warn'

    fig = make_subplots(rows=2, cols=3,
```

```
                        subplot_titles = ('Signifiant Wave Height',
'High Tide WL', '',
                                          'Critical Shear Stress',
'Erodability','Critical Velocity'),
                        vertical_spacing=0.12,
horizontal_spacing=0.1)
    fig.update_layout(title={
            'text': "OTE2C - Probabilistic module",  # Texte du
titre
            'x': 0.5,  # Position horizontale du titre (0-1)
            'y': 0.98,  # Position verticale du titre (0-1)
            'xanchor': 'center',  # Ancrage horizontal du titre
('left', 'center', 'right')
            'yanchor': 'top',  # Ancrage vertical du titre ('top',
'middle', 'bottom')
            'font': dict(size=36, family='Calibri')},  # Taille et
police du titre
        annotations=[pltly.layout.Annotation(text="Failure
probability = "+format(prob_fail)+" per
year",x=0.525,y=1.04,ay='top')],
        showlegend=True)
    fig.update_layout(margin=dict(t=135,b=50,l=50,r=50))
    fig.update_layout(images=[dict(
        source='data:image/png;base64,{}'.format(logoISL.decode()),
        xref="paper", x=0.02,
        yref="paper", y=1.13,
        sizex=0.1, sizey=0.1,
        xanchor="left", yanchor="top"),
        dict(

source='data:image/png;base64,{}'.format(logoPolder.decode()),
        xref="paper", x=0.1,
        yref="paper", y=1.12,
        sizex=0.12, sizey=0.12,
        xanchor="left", yanchor="top"
        )])
    fig.update_layout(legend_title_text="Failures distribution",
                      legend = dict(x=0.8, y=1,
traceorder="normal"),
                      legend_tracegroupgap = 15)


df_tmp=(df2.groupby(['SWH'])['pdens'].sum()/total_density).reset_ind
ex()
    fig.add_trace(pltly.Bar(x=df_tmp.iloc[:,0],
y=df_tmp.iloc[:,1]*100, name = 'SWH'), row=1, col=1)
    fig.update_xaxes(title_text= 'Signifiant Wave Height (m)',
row=1, col=1)
    fig.update_yaxes(title_text= 'percent (%)', row=1, col=1)


df_tmp=(df2.groupby(['HighTide'])['pdens'].sum()/total_density).rese
t_index()
    fig.add_trace(pltly.Bar(x=df_tmp.iloc[:,0],
y=df_tmp.iloc[:,1]*100, name = 'High Tide'), row=1, col=2)
```

```
    fig.update_xaxes(title_text= 'High Tide WL (m)', row=1, col=2)
    fig.update_yaxes(title_text= 'percent (%)', row=1, col=2)


df_tmp=(df2.groupby(['CritS'])['pdens'].sum()/total_density).reset_i
ndex()
    fig.add_trace(pltly.Bar(x=df_tmp.iloc[:,0],
y=df_tmp.iloc[:,1]*100, name = 'CritS'), row=2, col=1)
    fig.update_xaxes(title_text= 'Critical Shear Stress (Pa)',
row=2, col=1)
    fig.update_yaxes(title_text= 'percent (%)', row=2, col=1)


df_tmp=(df2.groupby(['Erodability'])['pdens'].sum()/total_density).r
eset_index()
    fig.add_trace(pltly.Bar(x=df_tmp.iloc[:,0],
y=df_tmp.iloc[:,1]*100, name = 'Erodability'), row=2, col=2)
    fig.update_xaxes(title_text= 'Erodability (cm3/N/s)', row=2,
col=2)
    fig.update_yaxes(title_text= 'percent (%)', row=2, col=2)


df_tmp=(df2.groupby(['CritV'])['pdens'].sum()/total_density).reset_i
ndex()
    fig.add_trace(pltly.Bar(x=df_tmp.iloc[:,0],
y=df_tmp.iloc[:,1]*100, name = 'CritV'), row=2, col=3)
    fig.update_xaxes(title_text= 'Critical Velocity (m/s)', row=2,
col=3)
    fig.update_yaxes(title_text= 'percent (%)', row=2, col=3)

    fig.write_html('OTE2C_Histograms.html')

# print("Significant Wave Height = ", SignifiantWaveHeight)
# print("High Tide Level =         ", HightideWaterLevel)
# print("Delta crest =       ", simple_config(SignifiantWaveHeight,
HightideWaterLevel, 2.0, 20))
# exit()

# Afficher le nom du navigateur par défaut

# ---- Loading CDF files
SWH_cdf = load_cdf('Hs_CDF.csv')
HTWL_cdf = load_cdf('Tide_CDF.csv')
CritV_cdf = load_cdf('CritVelo_CDF.csv')
CritS_cdf = load_cdf('CritShear_CDF.csv')
Erod_cdf = load_cdf('Erodability_CDF.csv')
# print(SWH_cdf[-2:,:])
# print(HTWL_cdf[:2,:])
# print(CritV_cdf[-2:,:])
# print(CritS_cdf[-2:,:])
# print(Erod_cdf[-2:,:])
# exit()

# ---- Creation of discrete grids
Resolution = 1000
```

```
SWH_grid = deform_cdf(SWH_cdf,0.5,Resolution)
HTWL_grid = deform_cdf(HTWL_cdf,0.5,Resolution)
CritV_grid = deform_cdf(CritV_cdf,2.0,Resolution)
CritS_grid = deform_cdf(CritS_cdf,2.0,Resolution)
Erod_grid = deform_cdf(Erod_cdf,2.0,Resolution)

# print(SWH_grid[-5:,:])
# print(1-np.sum(SWH_grid[:,1]))
# print(HTWL_grid[-5:,:])
# print(1-np.sum(HTWL_grid[:,1]))
# print(CritV_grid[-5:,:])
# print(1-np.sum(CritV_grid[:,1]))
# print(CritS_grid[-5:,:])
# print(1-np.sum(CritS_grid[:,1]))
plotting = False
logoISL = base64.b64encode(open('logoISL.png', 'rb').read())
logoPolder = base64.b64encode(open('Logo_Polder.PNG', 'rb').read())

if (len(sys.argv) > 2 and sys.argv[2]=="-r") or (len(sys.argv) > 1
and int(sys.argv[1] == 0)) :
    print("Loading last simulations")
    sim_results = pd.read_csv('Sim_details.csv', sep=';', header=0,
index_col=0)
    print("Columns loaded = ", sim_results.columns.tolist())
    nbr_sim = sim_results.shape[0]
    print("Number of simulations loaded = ", nbr_sim)
    if not(sim_results.shape[1] == 8) :
        print("Loaded simulations are corrupted, exiting")
        exit()
    print("")
    prob_fail = sim_results['fail_prob'].iloc[-1] #per day

    print("Fail probability at the end of the database = ",
prob_fail, "per year")
    total_density = sim_results['pdens'].sum()
    fail_density = (1-(1-prob_fail)**(1/365)) * total_density   #per
day
    if sim_results.shape[0] > 100 :
        failures = sim_results.loc[sim_results['delta_hcr'] < 0]
        print("Number of failures in loaded database = ",
failures.shape[0])
        point_size =
calc_point_size(failures['pdens']/total_density)
        fig = make_first_plot()
        plot_histograms(failures)

webbrowser.open("file://"+os.path.abspath("OTE2C_Histograms.html"))

webbrowser.open("file://"+os.path.abspath("OTE2C_ScatterPlot.html"))
        plotting = True
else :
    print("New simulations")
    if os.path.exists('Sim_details.csv'):
        os.rename('Sim_details.csv', 'Sim_details_last.csv')
    fail_density = 0
```

```
    total_density = 1e-40
    sim_results = pd.DataFrame(columns = ['SWH', 'HighTide',
'CritV', 'CritS', 'Erodability', 'delta_hcr', 'pdens', 'fail_prob'])
    sim_results.to_csv('Sim_details.csv', sep=';', index=True)



# Beginning of Monte-Carlo iterations
nbr_sim = int(sys.argv[1])

for i in range(nbr_sim):
    nrand_1 = np.random.randint(0, Resolution)
    nrand_2 = np.random.randint(0, Resolution)
    nrand_3 = np.random.randint(0, Resolution)
    nrand_4 = np.random.randint(0, Resolution)
    nrand_5 = np.random.randint(0, Resolution)
    SignifiantWaveHeight = SWH_grid[nrand_1,0]
    HightideWaterLevel   = HTWL_grid[nrand_2,0]
    Critvel       = CritV_grid[nrand_3,0]
    CritShear     = CritS_grid[nrand_4,0]
    Erodability   = Erod_grid[nrand_5,0]
    delta_hcr = simple_config(SignifiantWaveHeight,
        HightideWaterLevel,
        Critvel,
        CritShear,
        Erodability)
    pdensity = SWH_grid[nrand_1,1] * HTWL_grid[nrand_2,1]
    pdensity *= CritV_grid[nrand_3,1] * CritS_grid[nrand_4,1] *
Erod_grid[nrand_5,1]       # daily probability!
    total_density += pdensity
    if delta_hcr < -0.001:      # Failure criteria here
        fail_density += pdensity
    prob_fail = fail_density/total_density  #per day
    prob_fail = 1-(1-prob_fail)**365    #per year
    # Post-traitement
    nwsim = pd.DataFrame([[SignifiantWaveHeight, HightideWaterLevel,
        Critvel, CritShear, Erodability, delta_hcr,
        pdensity, prob_fail]],
        columns = ['SWH', 'HighTide', 'CritV', 'CritS',
'Erodability', 'delta_hcr', 'pdens', 'fail_prob'])
    sim_results = pd.concat([sim_results, nwsim], axis = 0,
ignore_index=True)
    if (i+1)%20 == 0 :
        duration = (time.time() - start_clock)/60
        print(i+1, "Prob =", prob_fail, \
        "\tTotal_time =", round(duration,2) , "min", \
        "\tRemaining = ", round((nbr_sim - i) / (1+i) * duration,2),
"min")
    # plotting
    if sim_results.shape[0] > 200 and (i+1)%40 == 0 :
        failures = sim_results.loc[sim_results['delta_hcr'] < 0]
        point_size =
calc_point_size(failures['pdens']/total_density)
        plot_histograms(failures)
        if plotting :
```

```
            update_scatter_map(fig)
        else :
            fig = make_first_plot()

webbrowser.open("file://"+os.path.abspath("OTE2C_Histograms.html"))

webbrowser.open("file://"+os.path.abspath("OTE2C_ScatterPlot.html"))
            plotting = True

sim_results.to_csv('Sim_details.csv', sep=';', index=True)
print("")
print("Probability of failure = ", prob_fail, "per year")
plot_histograms(failures)

# Plotting convergence
if len(sim_results['fail_prob']) > 1000 :
    plt.plot(sim_results['fail_prob'].iloc[1000:])
    plt.xlabel('Simulation index (-)')
    plt.ylabel('Failure probability (per year)')
    plt.title('Stability of Monte-Carlo simulations')
    plt.grid(True)
    plt.show()
```

D EFA and JET test results for the Hedwigepolder

D.1 EFA tests

For the EFA tests, five samples were taken close to the site of the wave overtopping tests, a few weeks prior to the tests. The locations are shown in Figure_ D.1.1.

Figure_ D.1.1 Locations were the samples for the EFA tests were taken, visible as holes in the slope to the left of the third wave overtopping tests (Figure 5.5 from Van Damme et al., 2023).

The erosion function graphs for all the tested samples are given in Figure_ D.1.2 to Figure_ D.1.11.

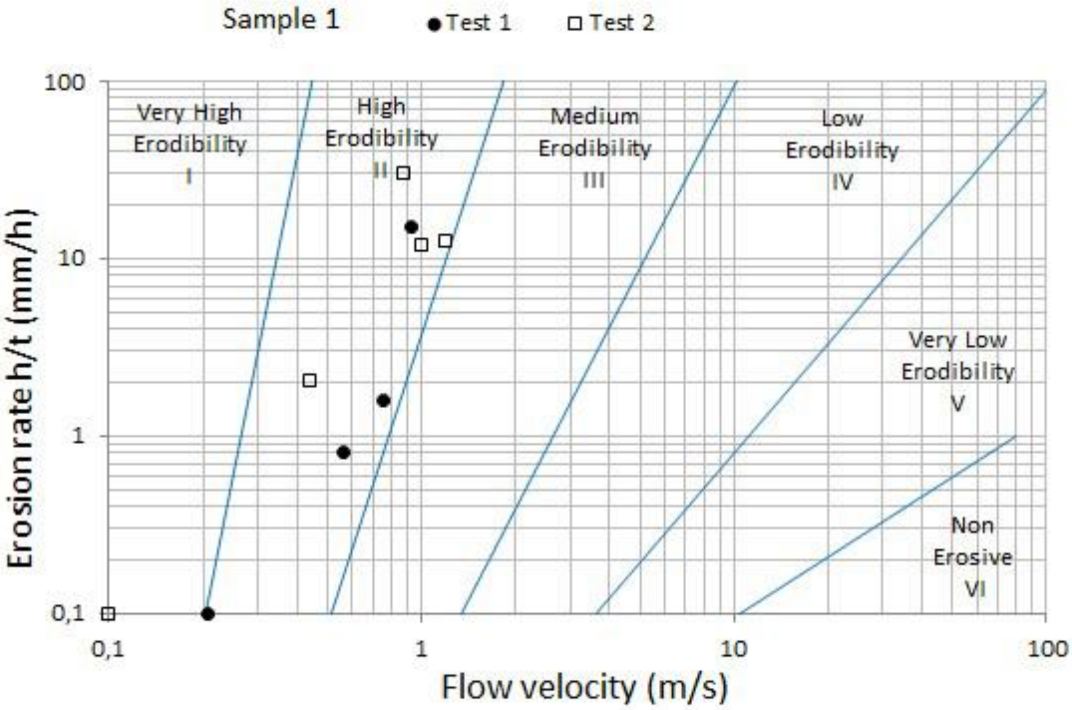

Figure_ D.1.2 Erosion function graph based on flow velocity for EFA sample 1 (Figure 5.8 (left) from Van Damme et al., 2023).

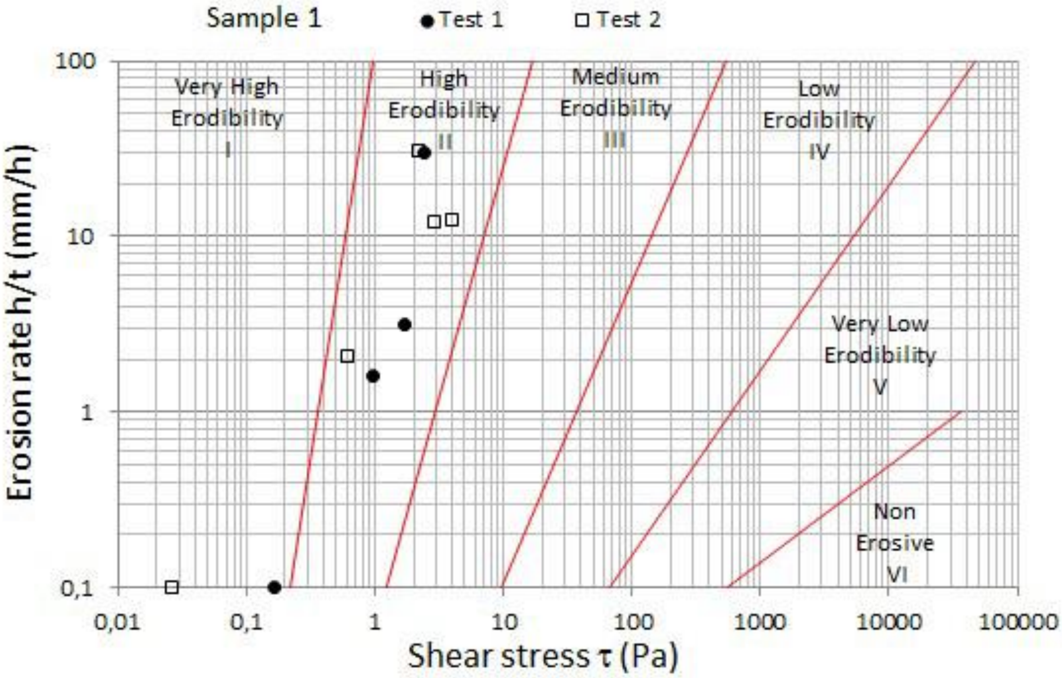

Figure_ D.1.3 Erosion function graph based on shear stress for EFA sample 1 (Figure 5.8 (right) from Van Damme et al., 2023).

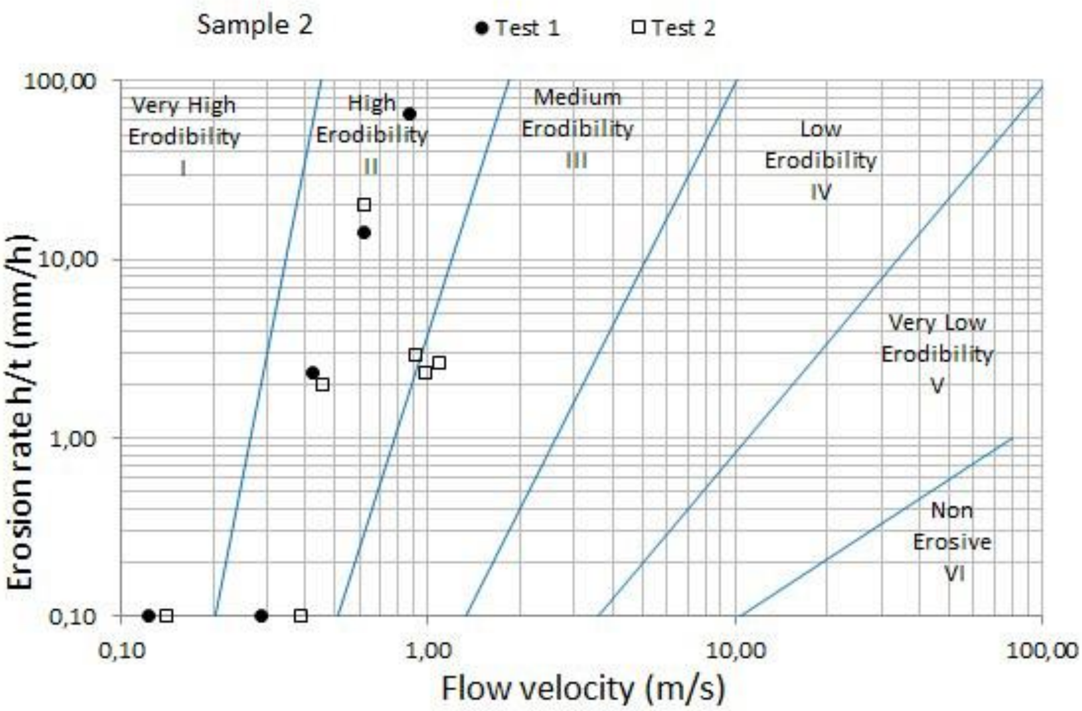

Figure_ D.1.4 Erosion function graph based on flow velocity for EFA sample 2 (Figure 5.9 (left) from Van Damme et al., 2023).

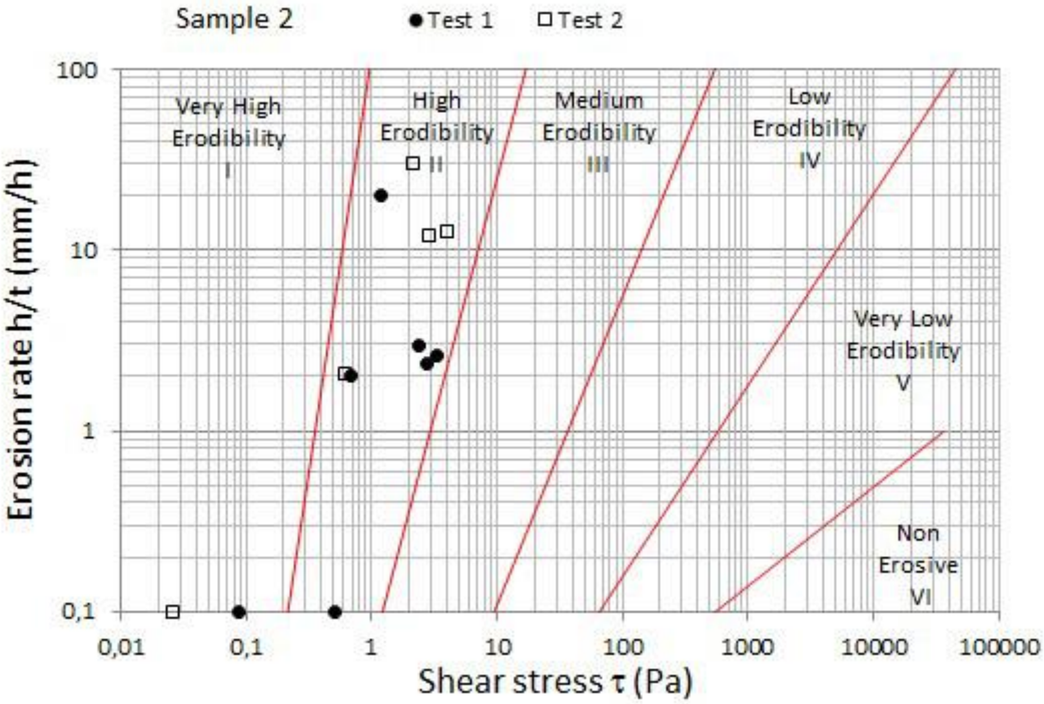

Figure_ D.1.5 Erosion function graph based on shear stress for EFA sample 2 (Figure 5.9 (right) from Van Damme et al., 2023).

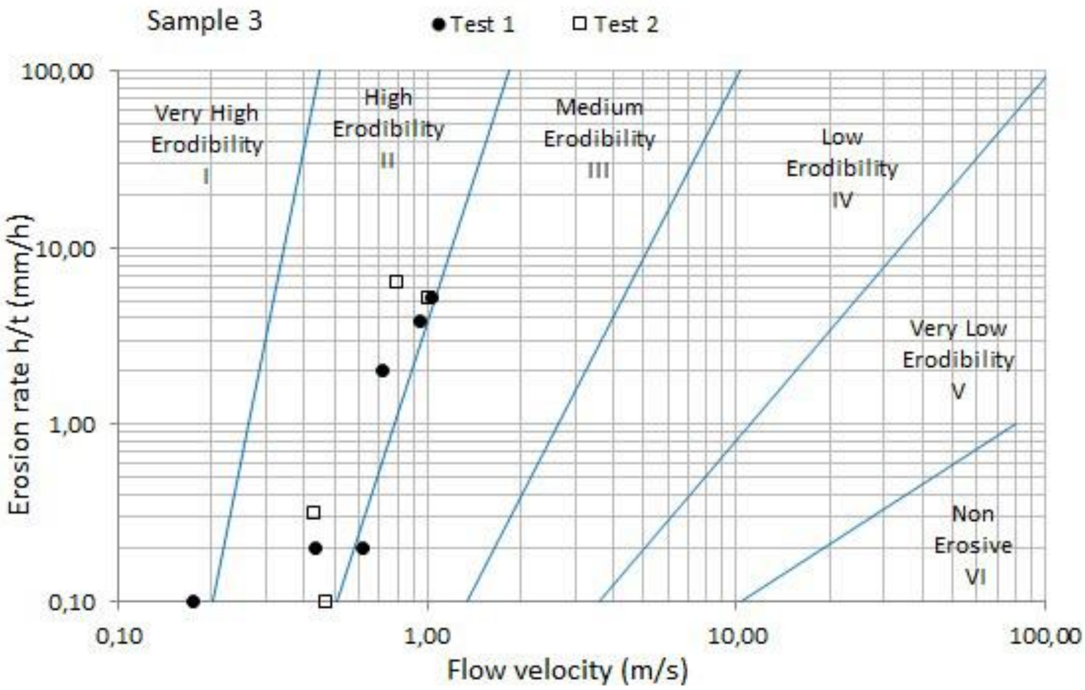

Figure_ D.1.6 Erosion function graph based on flow velocity for EFA sample 3 (Figure 5.10 (left) from Van Damme et al., 2023).

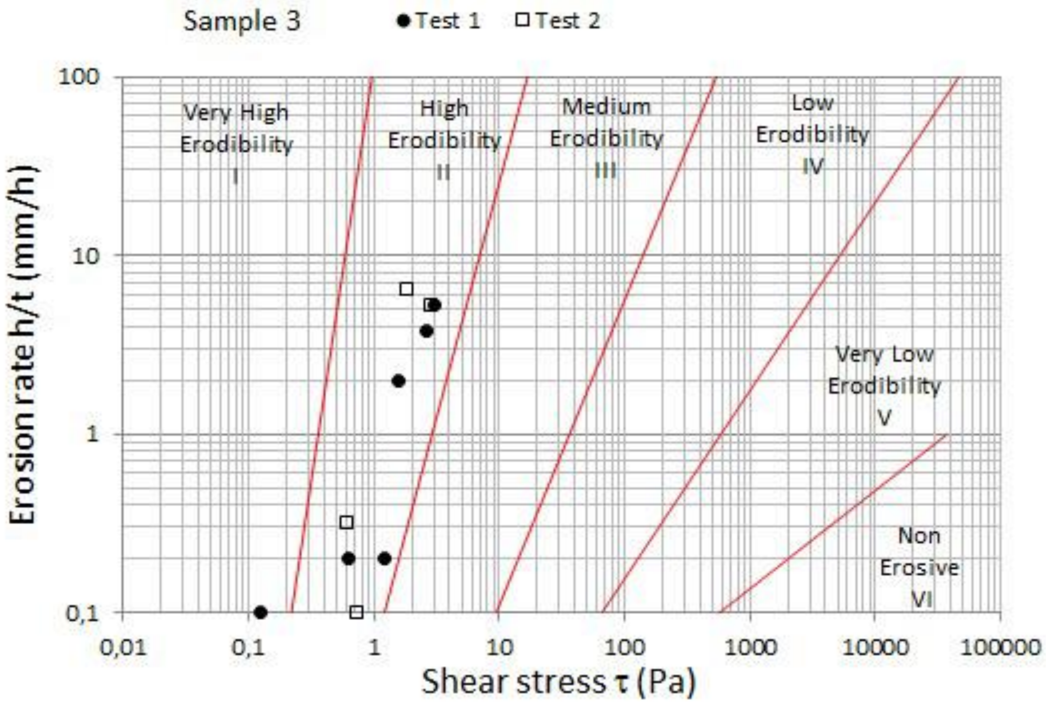

Figure_ D.1.7 Erosion function graph based on shear stress for EFA sample 3 (Figure 5.10 (right) from Van Damme et al., 2023).

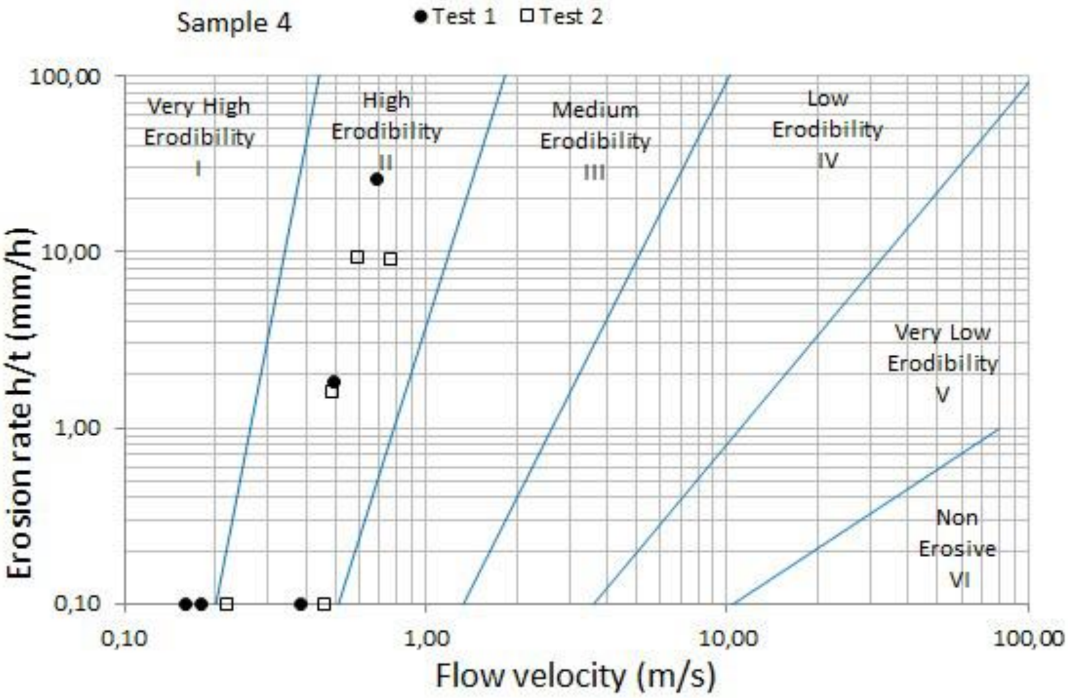

Figure_ D.1.8 Erosion function graph based on flow velocity for EFA sample 4 (Figure 5.11 (left) from Van Damme et al., 2023).

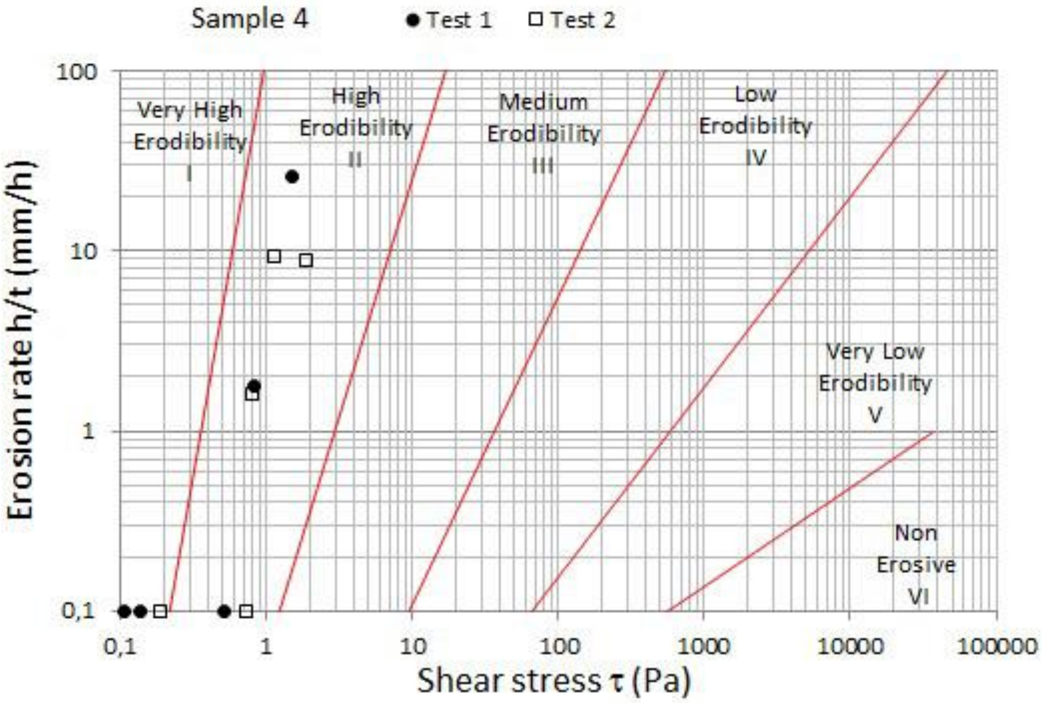

Figure_ D.1.9 Erosion function graph based on shear stress for EFA sample 4 (Figure 5.11 (right) from Van Damme et al., 2023).

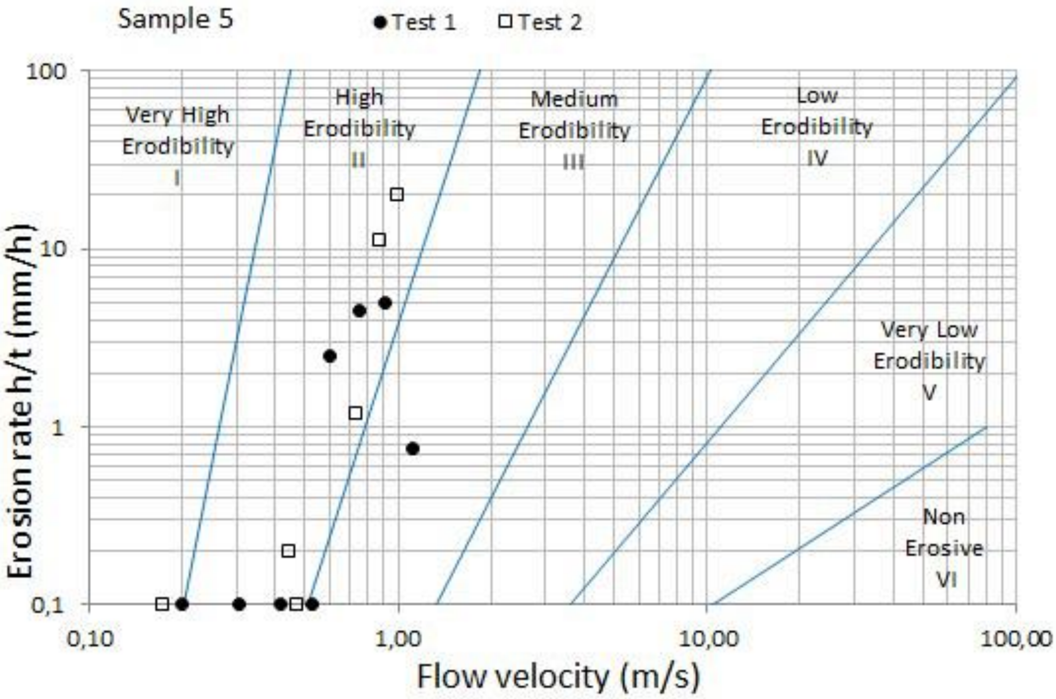

Figure_ D.1.10 Erosion function graph based on flow velocity for EFA sample 5 (Figure 5.12 (left) from Van Damme et al., 2023).

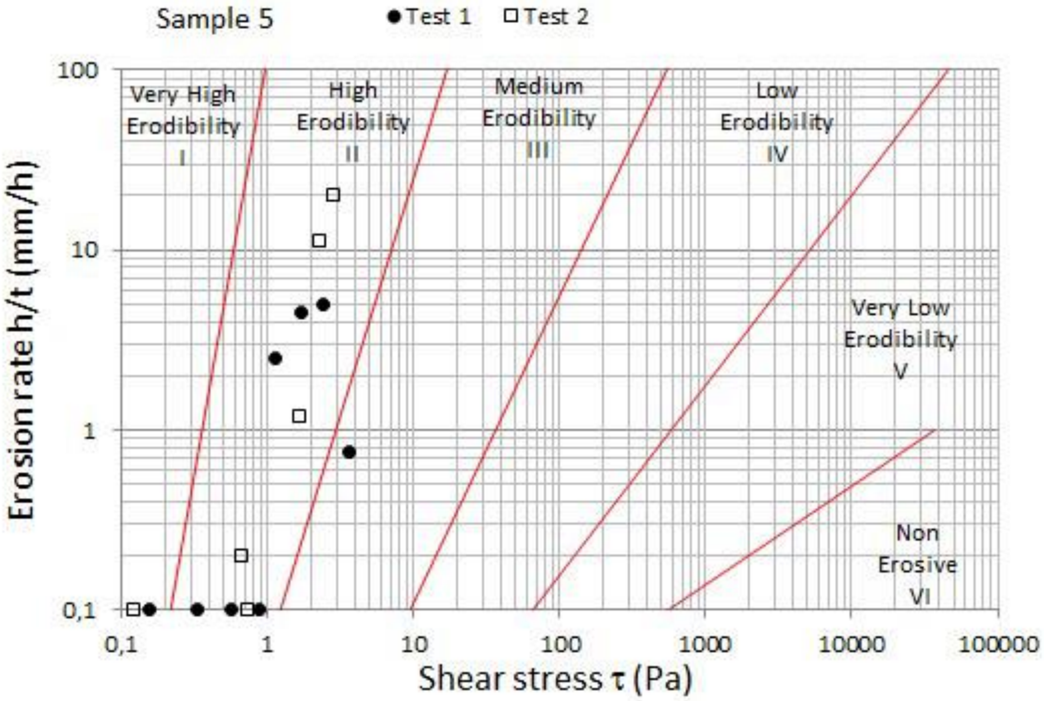

Figure_ D.1.11 Erosion function graph based on shear stress for EFA sample 5 (Figure 5.12 (right) from Van Damme et al., 2023).

Generally, the classification of ‘high erodibility’ applies to the results.

In Van Damme et al. (2023), a further analysis is done using an equation for the critical stress from Briaud (cited there). This equation includes the plasticity index, the median diameter, and the initial water content. Next, to determine an approximate value of the initial erodibility

K_d of the tested samples, the erosion function curves were plotted using linear scales for the erosion rate and each of the two parameters, flow velocity and shear stress. The curves are shown below in Figure_ D.1.12 to Figure_ D.1.21. A linear trend curve was chosen and a value for K_d was determined for R^2 values above 0.65. The obtained values are reported in Table_ D.1.1, after the figures. The ‘Equation 5.1’ mentioned in the header is the abovementioned equation from Briaud.

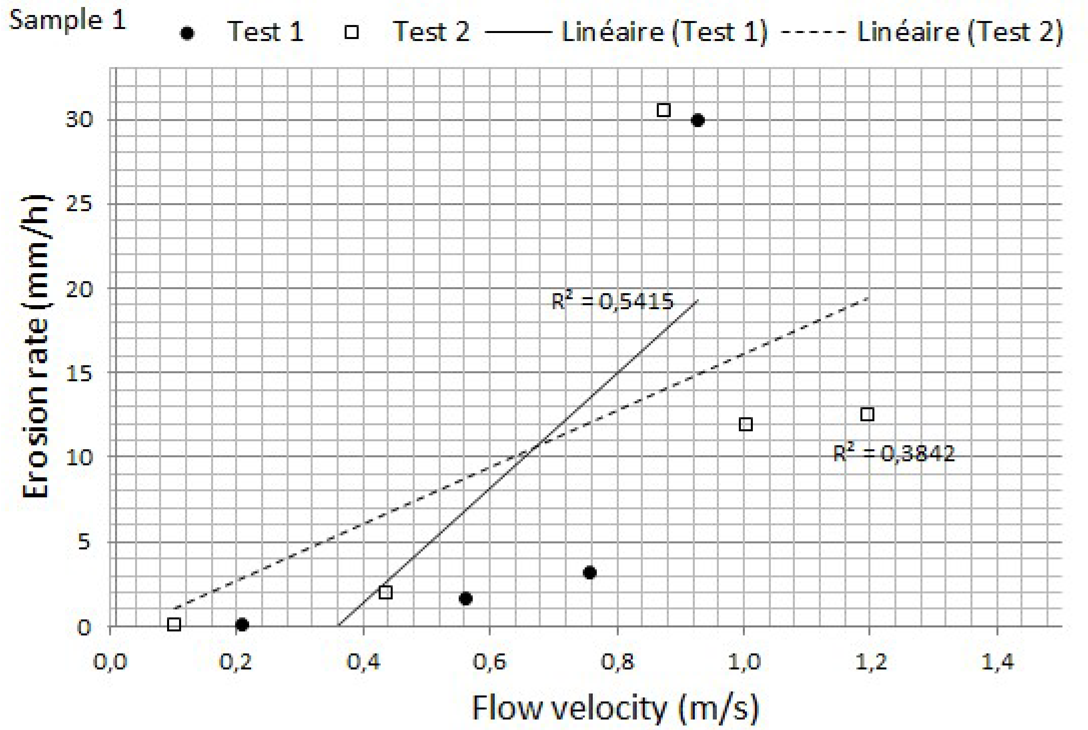

Figure_ D.1.12 Erosion function graph based on flow velocity for EFA sample 1 using linear scales (Figure 5.13 (left) from Van Damme et al., 2023).

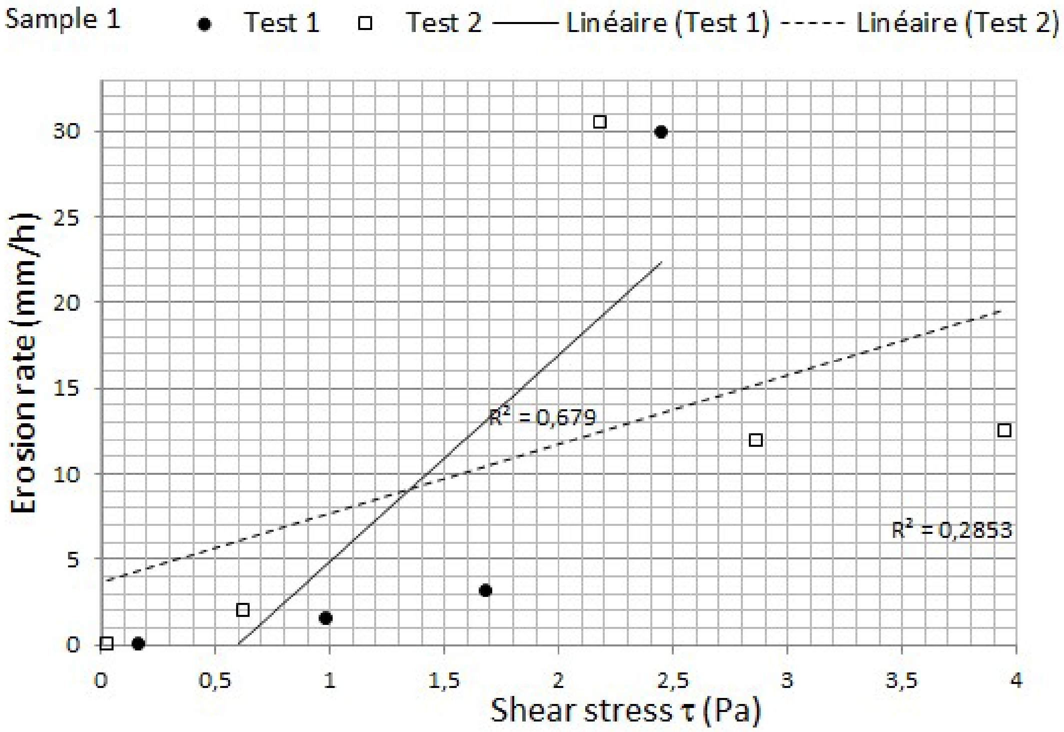

Figure_ D.1.13 Erosion function graph based on shear stress for EFA sample 1 using linear scales (Figure 5.13 (right) from Van Damme et al., 2023).

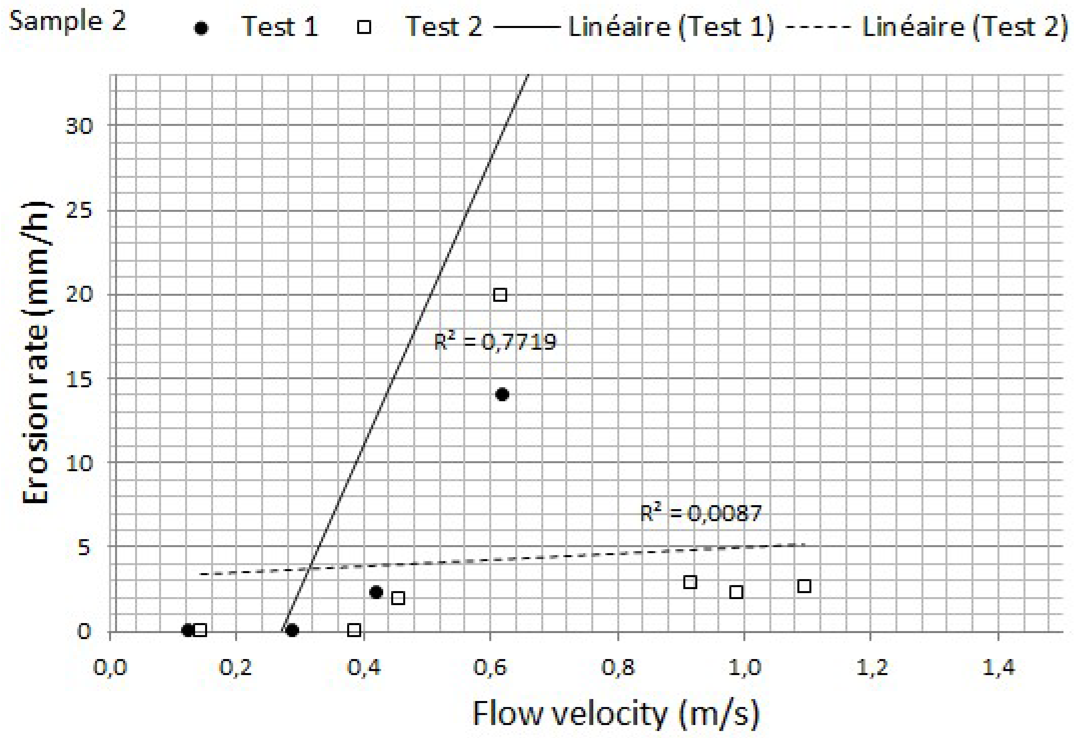

Figure_ D.1.14 Erosion function graph based on flow velocity for EFA sample 2 using linear scales (Figure 5.14 (left) from Van Damme et al., 2023).

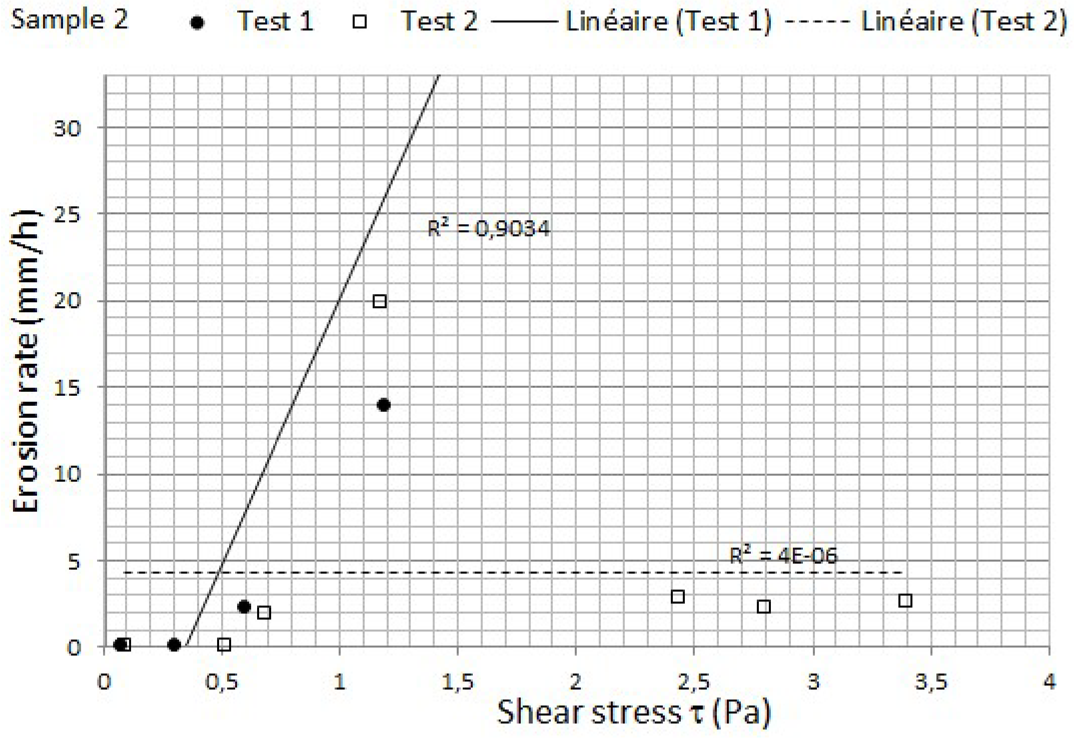

Figure_ D.1.15 Erosion function graph based on shear stress for EFA sample 2 using linear scales (Figure 5.14 (right) from Van Damme et al., 2023).

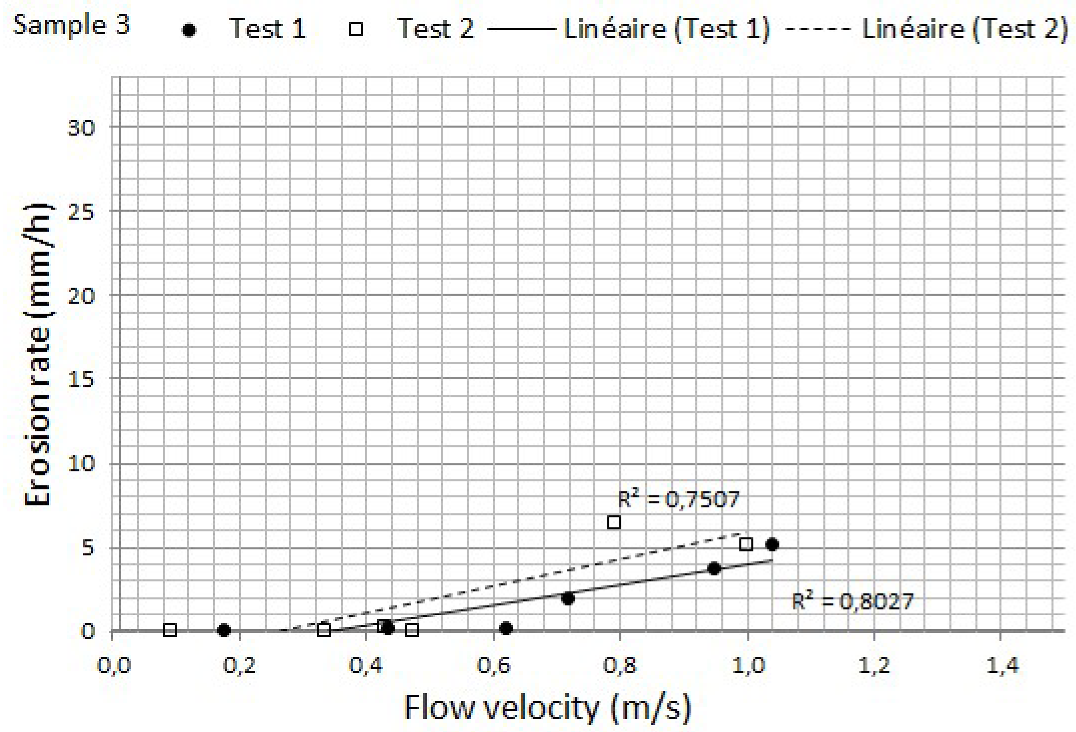

Figure_ D.1.16 *Erosion function graph based on flow velocity for EFA sample 3 using linear scales (Figure 5.15 (left) from Van Damme et al., 2023).*

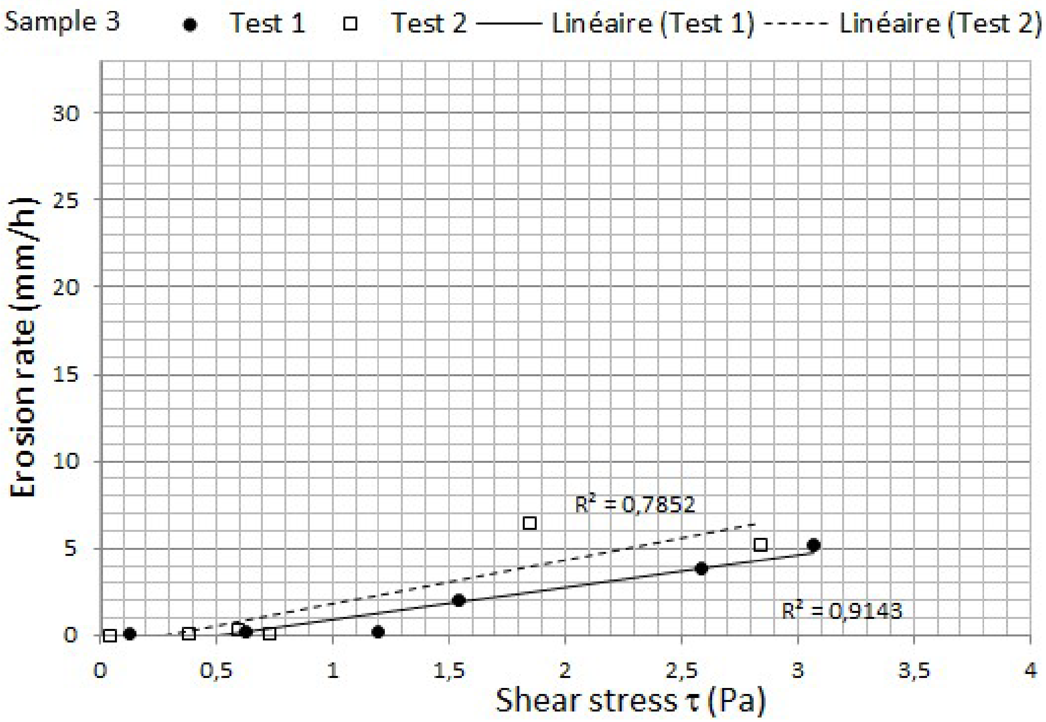

Figure_ D.1.17 *Erosion function graph based on shear stress for EFA sample 3 using linear scales (Figure 5.15 (right) from Van Damme et al., 2023).*

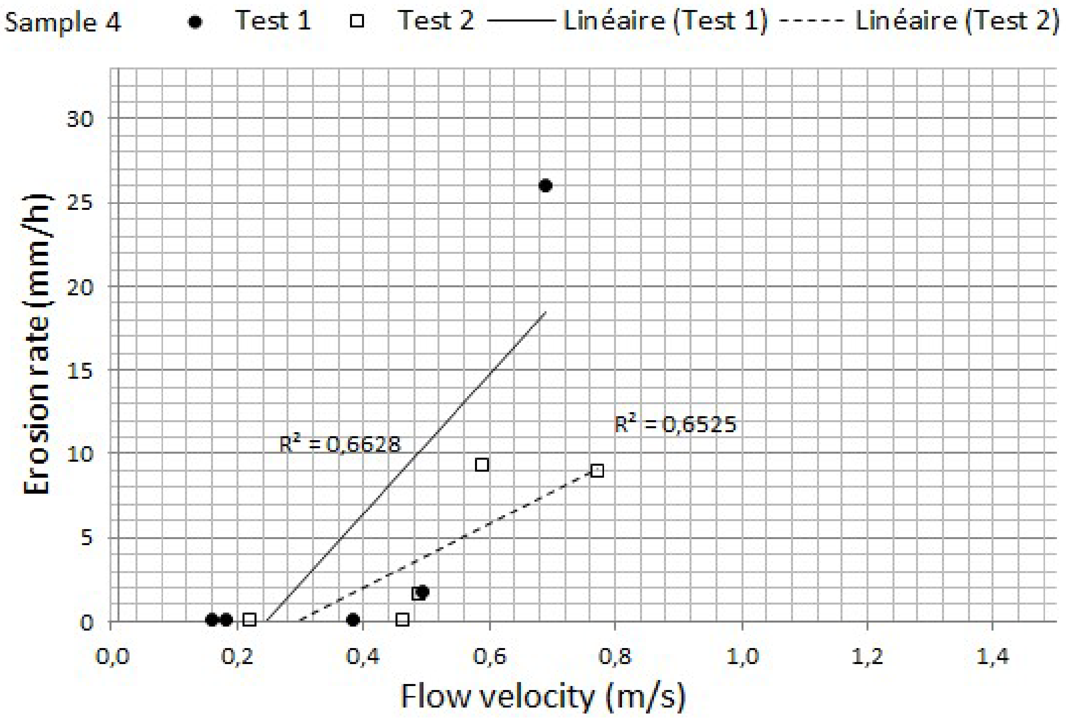

Figure_ D.1.18 Erosion function graph based on flow velocity for EFA sample 4 using linear scales (Figure 5.16 (left) from Van Damme et al., 2023).

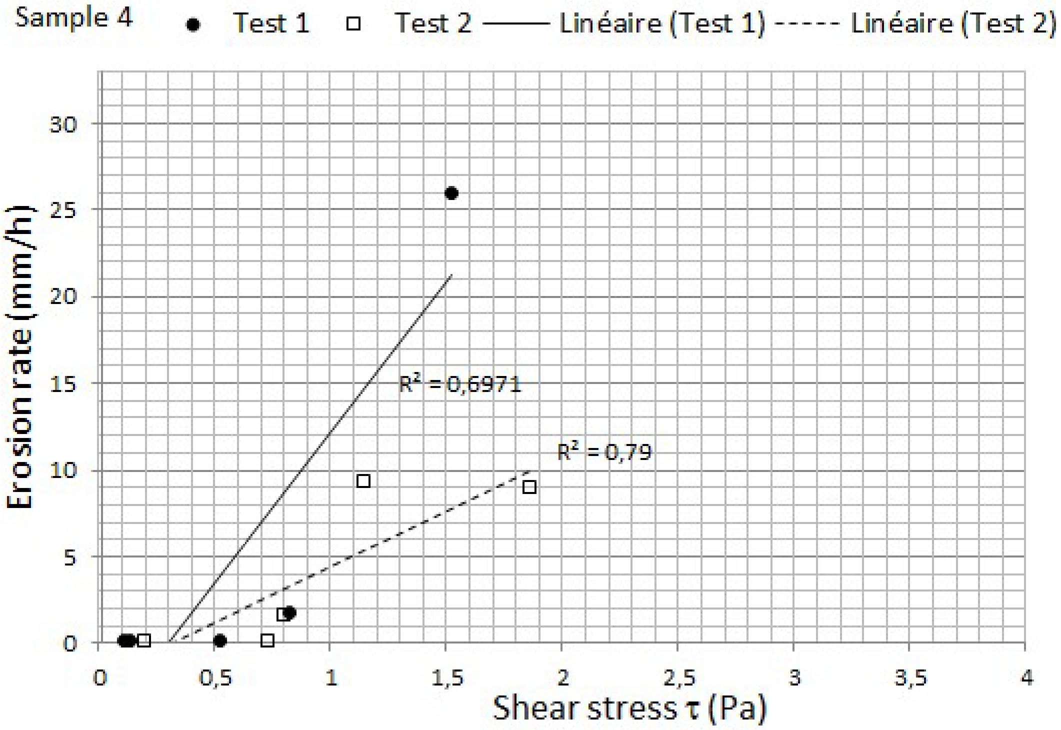

Figure_ D.1.19 Erosion function graph based on shear stress for EFA sample 4 using linear scales (Figure 5.16 (right) from Van Damme et al., 2023).

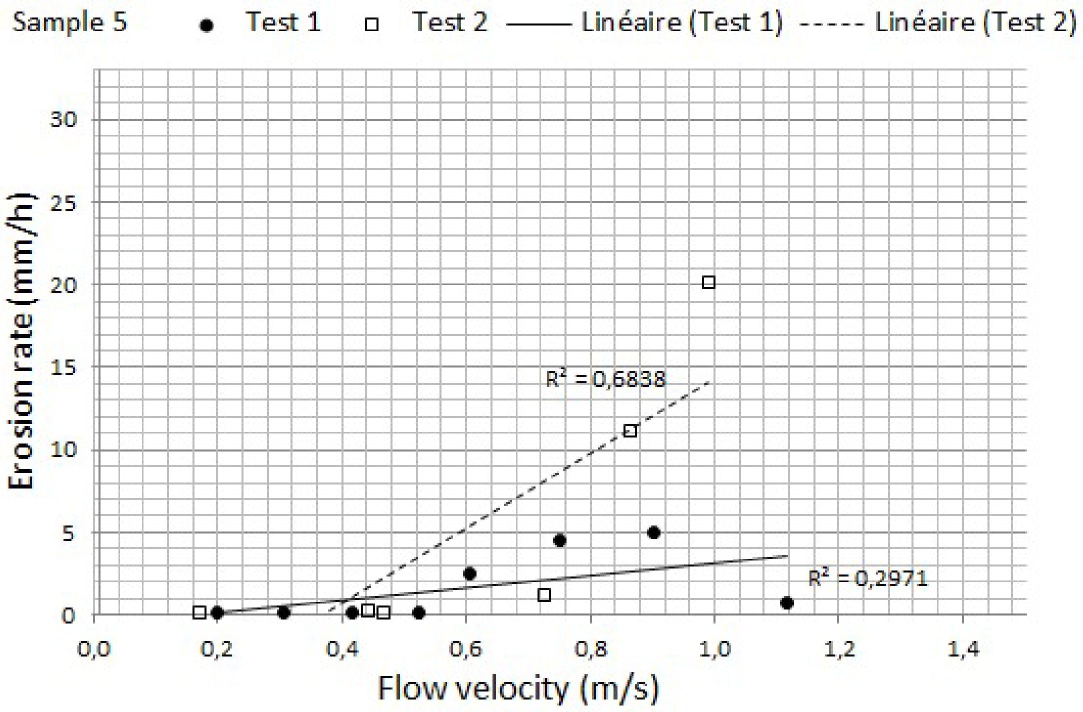

Figure_ D.1.20 Erosion function graph based on flow velocity for EFA sample 5 using linear scales (Figure 5.17 (left) from Van Damme et al., 2023).

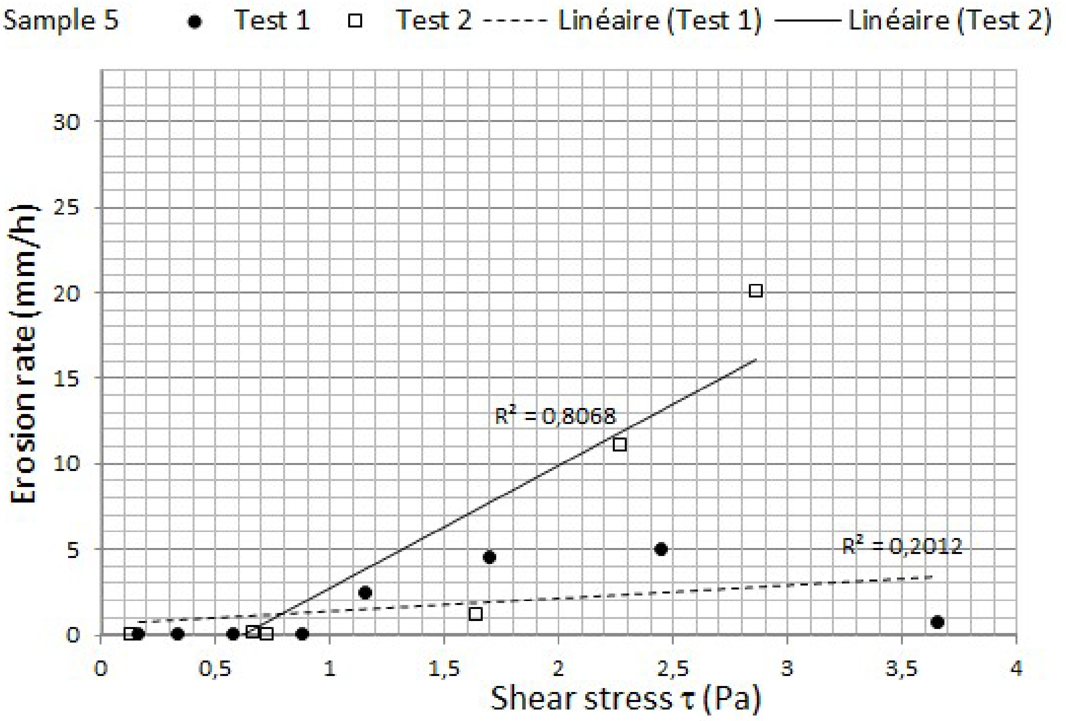

Figure_ D.1.21 Erosion function graph based on shear stress for EFA sample 5 using linear scales (Figure 5.17 (right) from Van Damme et al., 2023).

Table_ D.1.1 Critical flow velocity V_c, critical shear stress t_c and erodibility K_d for the five samples (Table 5.5 in Van Damme et al., 2023).

Sample	Identification	Test	V_c [m/s]	τ_c [Pa]	τ_c [Pa] (equation)	K_d [cm^3/Ns]
1	Clay soil with roots	1 2	0.2-0.6 0.1-0.5	0.2-1.2 0.2-0.7	0.2	12.14 -
2	Silty sand with roots and traces of rust	1 2	0.3-0.4 0.4-0.5	0.1-0.3 0.5-0.7	0.19	15.00 -
3	Grey silt with roots and traces of rust	1 2	0.2-0.4 <0.3	0.1-0.6 <0.5	0.45	1.86 -
4	Grey silt with roots	1 2	0.4-0.5 0.45	0.5-0.8 0.5-0.7	-	17.27 -
5	Grey clay with roots	1 2	0.1-0.4 0.4	1.0-1.2 0.6	0.47	6.82

According to Van Damme et al. (2023), the results obtained indicate a ‘high erodibility’ of the tested samples according to the classification proposed by Briaud and associated with the use of the EFA erodimeter. All the value of the critical shear stresses are lower than 1 Pa. The initial Kd value is not high, and this is considered to be related to the presence of roots in the samples tested.

D.2 JET tests

The samples for the laboratory JET tests were taken from a larger part of the Hedwigepolder and also the adjacent Prosperpolder. Figure_ D.2.1 shows all results as coloured dots. The green dot gives the test result in Section X, while the black dot gives the test result in Section XI. The transition between these two sections is between the right-most sampling location and the test location shown in Figure_ D.1.1. The samples for the JET tests were taken at a larger distance to the actual test site than the samples for the EFA tests.

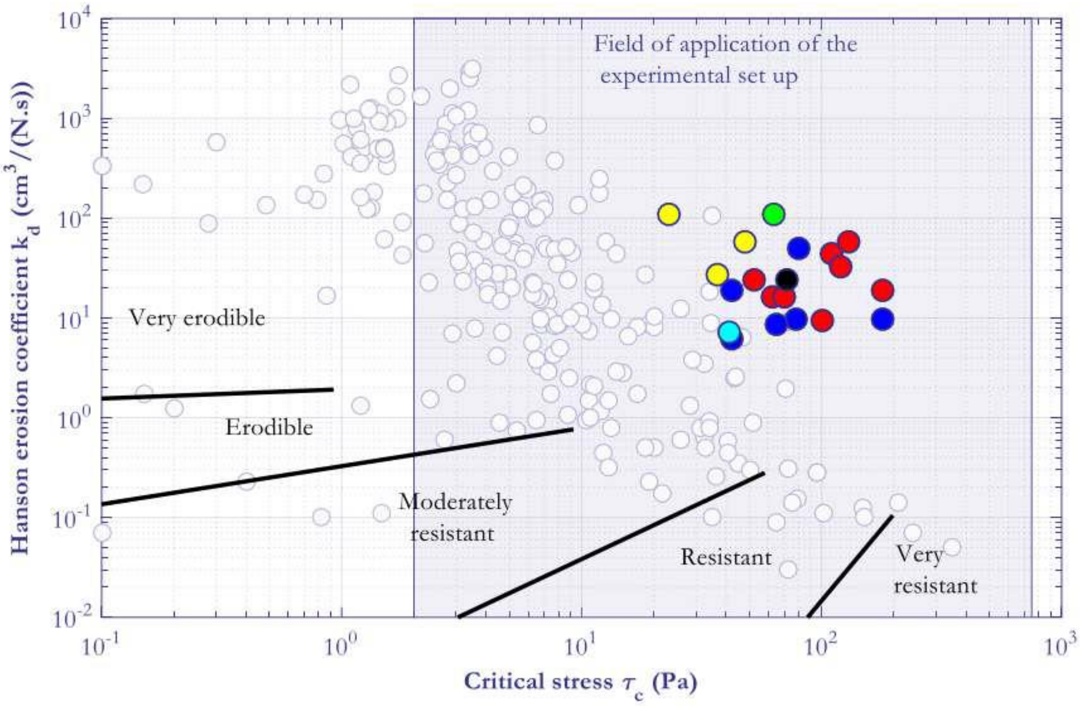

Figure_ D.2.1 Comparison of phase1 results from JET tests for each dike section along the Hedwige and Prosperpolders (Section II: yellow, IV: blue, VI: red, X: green, XI: black, XII: cyan) with Hanson diagram (white dots: worldwide database of contractor) (Figure 5.4 in Van Damme et al., 2023).

Van Damme et al. (2023) provides a table with a selection of the numerical results, reproduced here as Table_ D.2.1.

Table_ D.2.1 Selection of information form the Jet Erosion Test results (Table 5.2 in Van Damme et al., 2023).

TestID	Hydraulic head applied [mCe]	Associated stress range [Pa]	τ_c [Pa]	Confidence interval τ_c [Pa]	K_d [cm^3/Ns]	Confidence interval K_d [cm^3/Ns]
SX_E1_A	8.30 ± 0.12	63-121 41-61	63 36	51-76 19-53	110 5.2	84-130 2.8-7.7
SXI_E1_A	8.29 ± 0.11	67-135	72	56-89	24	17-31
SXII_E1_A	2.31 ± 0.05	41-88 30-37	41 30	28-55 23-38	7.2 0.82	5-9.3 0.31-1.3

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