EROSION PROCESS OF A CLAY REVETMENT WITH GRASS COVER ON COASTAL FLOOD DEFENCES BASED ON LARGE SCALE PHYSICAL MODEL TESTS

Vera van Bergeijk[1], Suzanna Zwanenburg[1], Jan-Willem Nieuwenhuis[2], Kees de Jong[2], Martin van der Meer[3], Werner Halter[3], Paul Buring[4], Mark Klein Breteler[1]

Clay and grass are natural building materials for flood defences that has been used in the Netherlands for centuries. However, the erosion process of the clay layer under wave loads is not well understood and is therefore usually not included in design and safety assessment methods in the Netherlands. Full scale physical model tests have been performed in the Delta Flume – the large scale wave flume at Deltares - with an undisturbed layer of clay and grass from sea dikes. Three measurement campaigns have been performed with 9 clay types and different geometries: slope steepness between 1:4 – 1:7 with and without a berm. The erosion process on the outer slope by wave impacts has been studied for significant wave heights up to 2 m and varying water levels. The results show that the erosion process of the clay revetment after erosion of the grass cover consists of two phases. During the first phase, the erosion mainly develops in depth. This erosion process shows a fast increase in erosion depth with a relatively small increase in eroded volume as the additional strength of the grass cover roots in this upper clay layer slows the growth of the erosion hole towards the dike crest. At a depth of around 50 cm, the grass cover roots have negligible influence on the erosion process allowing the erosion hole to grow faster towards the crest. A cliff is formed in the erosion hole and the second phase starts. During the second phase, the waves impact on the cliff resulting in cliff erosion and migration of the cliff towards the crest. The results of the physical model tests can be used to determine the erodibility of the different clay types and to develop formulas for the design and assessment of coastal flood defences built with local and natural materials.

Keywords: dike, levee, clay erosion, grass erosion, wave impact

INTRODUCTION

Climate change results in challenges for existing coastal flood defences such as increasing hydraulic loads due sea level rise and decreasing strength due to droughts. Moreover, the building of new structures and the reinforcements of existing structures are faced with challenges related to the greenhouse gas emissions and other sustainability goals. Clay and grass are natural building materials for flood defences that have been used in the Netherlands for centuries. Clay and grass are still commonly used as nature-inclusive design concepts are becoming more popular. Next to that clay can, for example, be gained from locally-dredged material and plays therefore a key role in innovative designs with reduced CO2 footprint during construction.

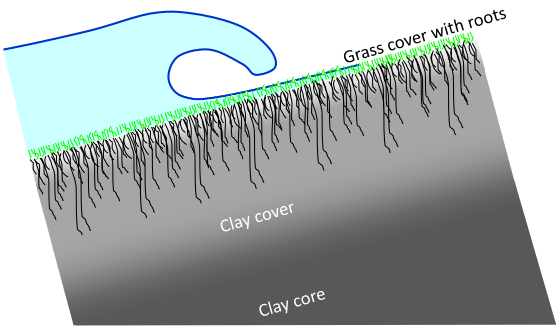

Figure 1 Left: Typical Dutch dike with a hard-covered lower slope and an upper slope of clay and grass. Right: Schematization of the clay revetment with a grass cover on the outer slope

A typical sea dike in the Netherlands is covered by a hard revetment – such as asphalt or a placed-block revetment – on the lower slope to protect the dike core against erosion by wave impacts (Figure 1). The upper slope has a cover of grass and clay (Figure 1). The grass cover is often able to withstand the load during wave run-up for a considerable duration, but this is not the case for the high peak pressures as the result of wave impacts. New flood defence concepts are becoming popular for their nature-inclusive character, such as the Wide Green Dike which is fully build of clay and has no hard revetment (Van Steijn and Klein Breteler, 2021).

Dike reinforcements are necessary in the future due to sea level rise that exposes the grass cover to wave impacts during extreme conditions. Several adaptation options are possible: (1) increase the height

[1] Deltares, The Netherlands
[2] Waterschap Nooderzijlvest, The Netherlands
[3] Fugro, The Netherlands
[4] Wetterskip Fryslân, The Netherlands

of the hard revetment, (2) reduce the wave impacts with a foreshore, berm or gentle slope, or (3) increase the thickness of the clay layer. The focus of this paper is on the third option. Limited knowledge is available on the erosion process of clay on the outer slope by wave impacts, and therefore the clay layer was not included by default in the safety assessment of dikes in the Netherlands.

The goal of this study is to obtain insights in the erosion process of clay with grass covers on coastal flood defences using large scale physical model tests. Three measurement campaigns have been performed between 2020 and 2024 in the Delta Flume at Deltares. Grass and clay covers were collected from existing dikes along the Dutch Wadden Sea. Several clay types and geometries have been tested under wave attack representative for existing levees and innovative designs. The results of the physical model tests can be used to develop formulas for the design and assessment of coastal flood defences built with local and natural materials which can be seen as clay.

This paper is structured as follows: first, the physical model tests are described including the model setup and test program. Next, the observations during the physical model tests are described and used for a general description of the erosion process in the results. The application of these results are discussed and finally the conclusions are stated.

PHYSICAL MODEL TESTS

A physical model was built in the Delta Flume of Deltares at model scale 1:1 to determine the erodibility and the erosion process of clay with a grass cover (Figure 2). The upper slope consisted of grass on top of a clay cover and was subjected to extreme waves with significant wave heights up to 2.0 m. The erosion process of clay on the outer slope by wave attack was studied during three test campaigns (Klein Breteler, 2021; Van Steijn and Klein Breteler, 2021; Van Bergeijk, 2023).

Figure 2: Photo of the physical model tests with clay and grass covers in the Delta Flume.

Firstly, in 2020 and 2021 six test series (K1-K6) were performed with varying geometry and three clay types from dikes along the Wadden Sea dike (Table 2; Klein Breteler, 2021). In this test campaign, the effect of a berm and the transition from the hard lower slope to the upper slope of grass and clay on the erosion process was investigated.

The second test campaign in 2021 was related to the Wide Green Dike project – a dike consisting of clay and grass along the entire outer slope where the wave impacts are reduced by the gentle slope of 1:7 – 1:8 (Van Steijn and Klein Breteler, 2021). The effect of a gentle slope on the erosion process was studied using four clay types: two types of unstructured clay from a clay ripening project and two types of structured and undisturbed clay from existing dikes. Two test series (B1-B2) have been performed, where two clay types were tested simultaneously.

The effect of clay structure on the erosion process was further investigated during two test series (EK1-EK2) in the recent test campaign “Dubbele Dijk” from 2023 (Van Bergeijk, 2023). The hypothesis was that well-compacted clay from the dike core is less erodible than the clay cover layer that is subject to weathering due to seasonal weather influences and biological activity. Therefore, clay blocks were collected with a clay cover and grass cover (as usual) and from the clay core at a depth of 1.5-2.5 m. Additionally, tests with varying water levels were performed to study the effect of tides and storm surges on the erosion process.

Model set-up

Figure 3 shows a typical cross-section of the physical model tests. The lower slope consist of a smooth hard revetment and the upper slope consists of the clay blocks (with grass). The core of the dike is made of sand and the clay blocks are placed on a layer of mixed and compacted clay on top of geotextile. The transition from the hard cover to the grass cover is chosen sufficiently low so the transition does not influence the erosion process. For the first measurement campaign, the transition was around the still water line to specifically determine the effect of the transition. Moreover, four geometries in this measurement campaign included a berm. The inner slope and (part of) the crest are covered with a hard revetment.

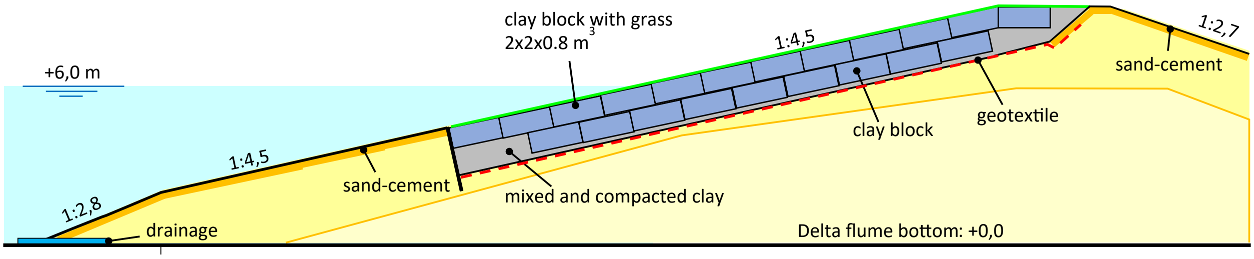

Figure 3 Cross-section of the physical model tests of test series DD1.

Full scale models are performed to obtain a realistic representation of the clay structure and grass cover. Blocks of clay are collected from an existing dike and transported to the Delta Flume using steel frames of 2 m x 2 m wide and 0.8 m deep (Klein Breteler et al., 2012). Firstly, the side walls are pushed into the slope (Figure 4). Next, the clay around the frame is excavated and the bottom plate is pushed underneath the frame (Figure 5). The frame including the clay and grass cover is lifted into a truck and transported towards Deltares. The clay blocks are collected perpendicular to the dike slope.

An almost seamless clay cover with grass is constructed in the Delta flume using the following procedure:

- The block is moved slowly downward along the slope until the gap with the lower block is as small as possible.
- The lower side wall is removed (Figure 6, left).
- The bottom plate is removed using a winch on a frame. Simultaneously, the block is pushed downward to close the gap with the lower-placed block (Figure 6, right).
- The upper side wall is removed.
- The gap between the clay block and the wooden side wall is filled using sand-cement and rebar.

Figure 4 Pushing in side walls of the steel frame into the dike slope

Figure 5 Excavation of the steel frame and pushing the bottom plate underneath the frame.

Figure 6 Removal of the side wall and the bottom plate in the Delta flume

Table 1. Clay characteristics (Klein Breteler, 2024)

Clay Type	Lutum content (<2µm) [%]	Sand content (>63 µm) [%]	Plastic limit [%]	Liquid limit [%]	Consistency index [-]	Dry density [kg/m^3]
Dubbele Dijk - cover	30.7	36.4	18.5	39.7	0.3	1369
Dubbele Dijk - core	33.8	25.4	18.7	36.4	0.7	1558
Valgenweg	40.3	25.3	30.6	87.1	0.7	1104
Klutenplas	45.4	9.9	36.3	89.4	0.7	1074
Dollarddijk	44.2	16.0	30.7	74.0	0.8	1191
Blija2021	43.8	8.6	30.4	67.2	0.8	1401
Lauwersmeerdijk	24.3	39.9	22.7	42.4	1.1	1424
Holwerd	24.8	31.3	19.5	36.6	1.1	1603
Blija2020	44.1	13.6	23.6	55.2	1.0	1494

The unstructured clay of the Valgenweg and Klutenplas in the Wide Green Dike campaign were constructed using 10 layers with a thickness between 15 and 20 cm parallel to the slope. The clay is compacted using machinery (Van Steijn and Klein Breteler, 2021). Experience has learned that it is important that a.o. the clay has the correct water content during the construction (consistency index > 0.75). It is difficult to compact clay with a too high water content, resulting in a high erosion rate. The clay characteristics of the eight clay types that were tested during the physical model tests are summarized in Table 1.

Test program

The model was loaded by extreme waves with significant wave heights up to 2.0 m with a wave steepness sop of approximately 0.04. The test conditions are summarized for each test series in Table 2. The wave conditions during individual tests can be found in the measurement reports (Klein Breteler, 2021; Van Steijn and Klein Breteler, 2021; Van Bergeijk, 2023). The wave conditions are determined using three wave height meters near the wave board. The wave conditions are also measured near the toe of the dike (Figure 7). The erosion during each test is measured using a laser scanner. Video cameras are used to document the tests and study the erosion process.

Table 2. Test series in the Delta Flume including the water level h, the significant wave height H_{m0} and the steepness of the outer slope cot(α).

Test series	Clay type	h [m]	Hm0 [m]	cot(α) [-]	Berm
EK1	Dubbele Dijk	5.0 – 7.0	1.28 – 2.02	4.5	No
EK2	Dubbele Dijk	6.0 – 6.2	1.54 – 1.99	4.5	No
B1	Valgenweg & Klutenplas	6.4	1.21 – 2.07	7	No
B2	Dollarddijk & Blija2021	6.4	1.51 – 2.05	7	No
K1	Lauwersmeerdijk	6.5	1.94 – 2.04	4	Yes
K2	Holwerd	6.4 – 6.65	1.92 – 2.02	5	Yes
K3	Holwerd	6.65 – 6.75	1.93 – 1.95	5	Yes
K4	Blija2020	5.90 – 6.65	1.67 – 2.08	4	Yes
K5	Holwerd	6.4	1.98 – 2.08	5	Yes
K6	Holwerd	5.90 – 6.65	1.53 – 2.11	5	No

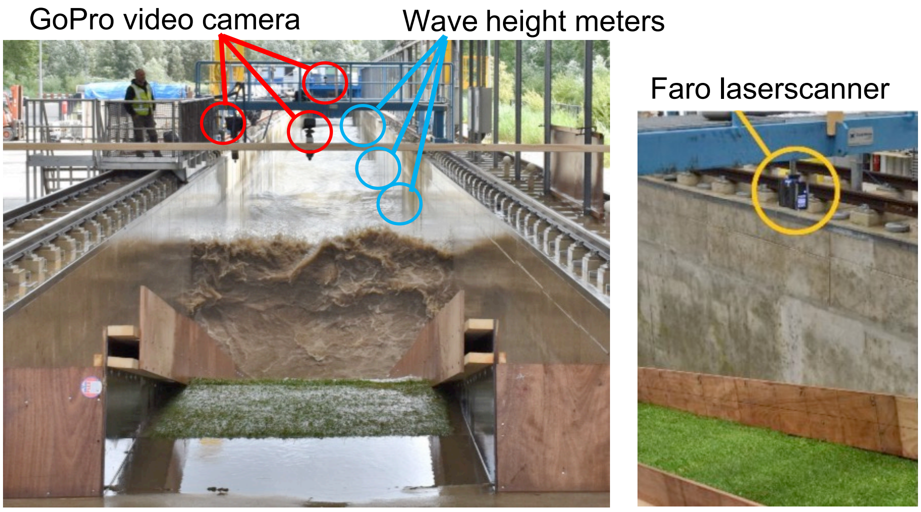

Figure 7 Instrumentation in the Delta Flume.

RESULTS

Physical model tests

An example of the erosion hole (development) during the test series can be found in Figures 9, 10 and 11. Figure 9 shows that the erosion starts at the transition from the hard revetment to the grass cover for the first measurement campaign. With these results the influence of the transition on the upper slope on the erosion process is studied, since no erosion was observed for the other two measurement campaigns where the transition was located below the wave impact zone (Figures 10 and 11).

Figure 8 Model set-up of test series K1 with clay type Lauwersmeerdijk with the erosion process halfway the test series and at the end of the test series.

Figure 9 The Wide Green Dike model set-up with two clay types: Blija2021 (left side) and Dollarddijk (right side) at the start and end of test series B2

Figure 10 The model set-up of test series EK1 and the final erosion hole of the measurement campaign Dubbele Dijk.

Two clay types were tested simultaneously during the Wide Green Dike set-up (Figure 10). The final result shows that the Dollarddijk clay is almost eroded completely, while very little clay erosion of the Blija2021 clay is observed. It can be concluded that the erodibility of the Dollarddijk is much larger than the erodibility of the Blija2021 clay.

For each test of each test series, the erosion volume and the maximum erosion depth is determined (Klein Breteler, 2021; Van Steijn and Klein Breteler, 2021; Van Bergeijk, 2023). Figure 12 shows the results of the EK1 test series (Figure 11) as function of the test series duration. It can be seen that during the first four hours, the erosion develops in depth while the erosion volume does not change significantly. In the next stage, the erosion volume increases over time, and the erodibility of the clay can be determined from the erosion rate. These two erosion phases were also observed during the other test series.

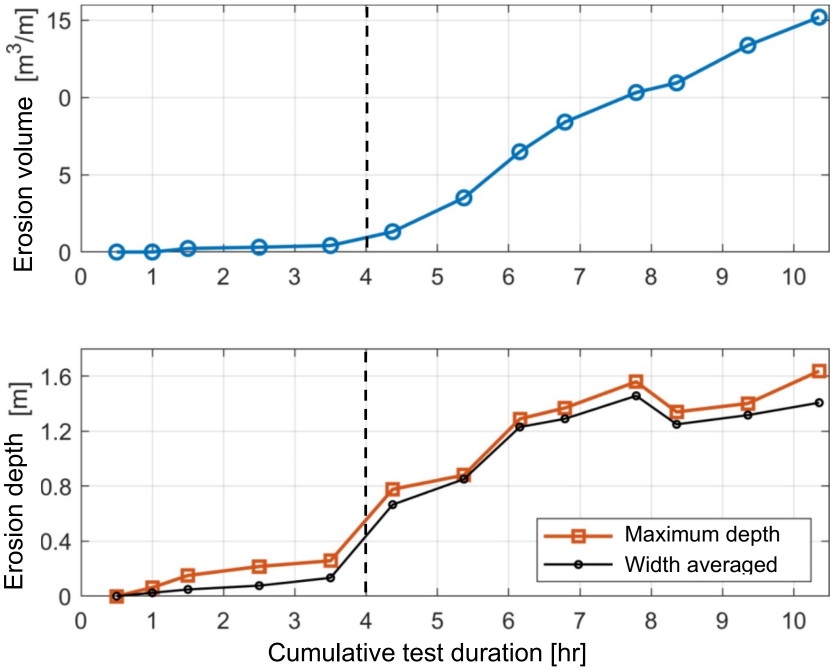

Figure 11 The measured erosion volume and measured maximum erosion depth during test series EK1. The dashed line indicated the transition between phase 1 and phase 2 erosion.

Erosion Process

The physical model tests showed that the erosion process of a clay cover with grass on the outer slope consist of three phases (Figures 13 and 14). Firstly, the grass cover is eroded, where the grass cover is defined as the upper 15-25 cm of the cover layer (Figure 1). The strength of the grass cover determines the erosion resistance and erodibility of this upper layer.

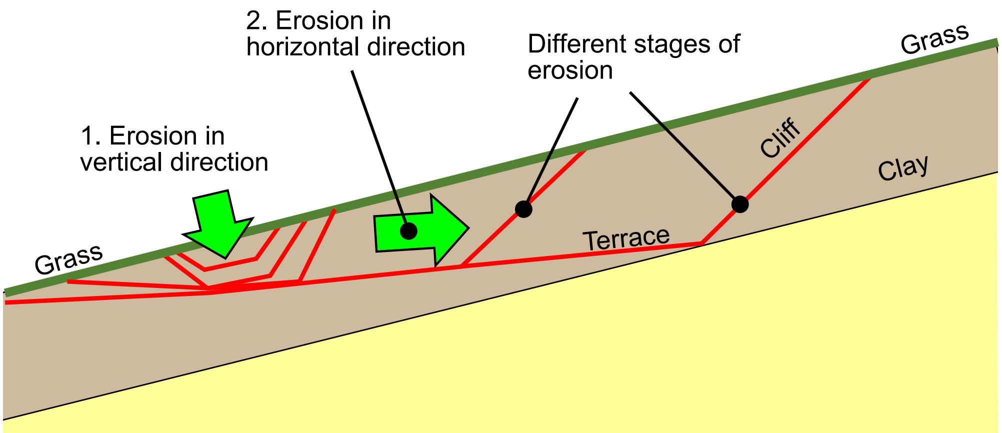

Figure 12 The erosion process of a clay cover on the outer slope by wave impacts

Next, the clay cover starts to erode. During the first phase of the clay erosion process, the erosion mainly develops in depth. This erosion process shows a fast increase in erosion depth with a relatively small increase in eroded volume as the additional strength of the grass cover roots in this upper clay layer slows the growth of the erosion hole towards the dike crest.

The second phase starts when the erosion depth has progressed to around 50 cm depth. At this depth, the grass cover roots have negligible influence on the erosion process allowing the erosion hole to grow faster towards the dike crest. A cliff has formed on which high hydraulic loads are exerted. This results in erosion of the base of the cliff: the cliff starts to migrate towards the crest and a relatively gentle terrace is formed. The erosion process in this second phase results in an accelerated increase in erosion volume.

The increase in erosion depth in this phase is generally slower and is the result of the erosion hole with terrace that moves towards the crest. The erodibility depends on the strength of the clay layer.

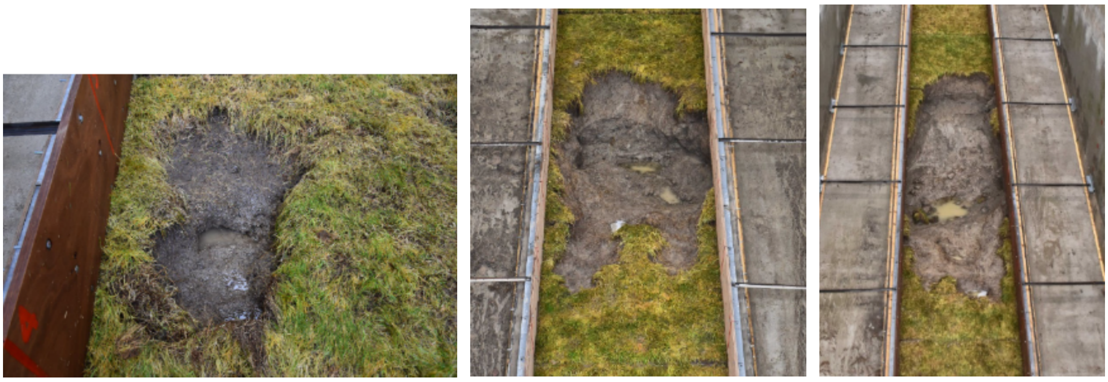

Figure 13 Photos of the three phases of the erosion process during test series EK2. Phase 0: grass cover failure with a damage of 28 cm depth. Phase 1: deepening of the erosion hole to a depth of about 0.6 m and the start of a small cliff forming. Phase 2: cliff erosion and formation of a terrace.

The transition on the upper slope from a hard revetment to the grass and clay cover influences the erosion process (Figures 9 and 15). The erosion starts at the transition, where the grass cover is eroded. Two similar erosion phases of the clay erosion process are identified. However, behind the transition a shadow zone is formed with limited erosion as result. Water stays in the erosion hole behind the transition, that dampens the wave loads and reduced the amount of erosion.

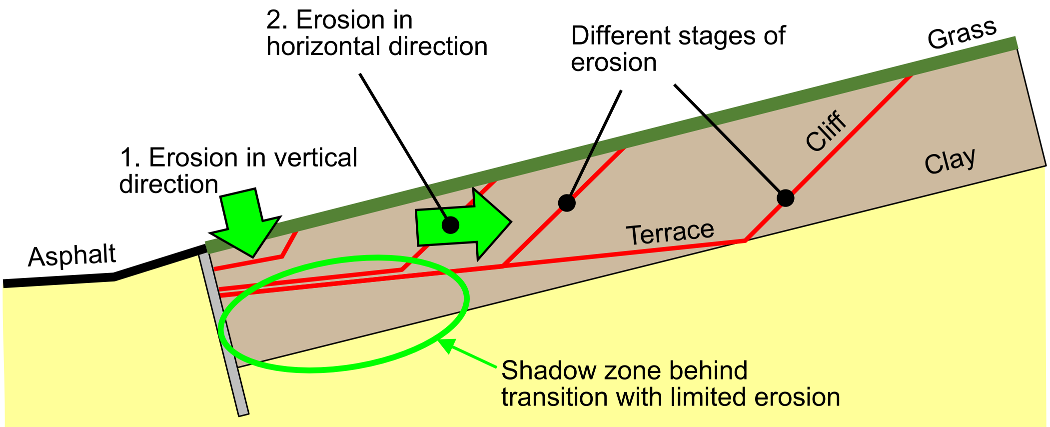

Figure 14 The erosion process of a clay cover on the outer slope by wave impacts with a transition from a hard revetment to the grass cover on the upper slope

APPLICATIONS

The physical model results can be used to develop formulas to calculate the erosion depth or erosion volume during a storm. As a first step, the wave conditions need to be translated to the hydraulic load on the clay cover. This is mainly done using numerical models.

- It was hypothesized by Klein Bretler et al. (2012) that the peak pressure on the cover layer is the main driver of the erosion process. Numerical simulations have been performed for large scale model tests by Mourik (2015) and Kaste et al. (2015) to develop an erosion formula. A similar method was used by Irias Mata et al. (2023) for the Wide Green Dike Project and will also be used in the analysis of these large scale physical model tests.
- Another type of erosion model was used by Kobayashi and Weitzner (2015) that uses the excess work as load description. The excess work is proportional to the third power of the flow velocity, and therefore the flow velocity is the main driver in this erosion model. The flow velocity is calculated based on the dissipation rate computed with the cross-shore numerical model CSHORE (Kobayashi et al., 2010).

- The flow velocity is also used as the erosion driver in the cumulative overload method for grass cover erosion due to wave run-up in the Dutch safety guidelines (Steendam et al., 2016). This erosion model is not valid in the wave impact zone and is only applicable to a dike surface with significantly small erosion holes (depth < 20 cm).

Such erosion formulas can be used to calculate the erosion volume and the erosion depth during a storm. In the Netherlands, the design and safety assessments are based on failure probabilities. This required as probabilistic model, for example the model presented by Van Bergeijk and Zwanenburg (2023) that can be used to calculate the required thickness of the clay and grass revetment. The required thickness is the main design parameter and depends on the erodibility of the clay.

The physical model tests have shown that the erodibility of the tested clay varies significantly, as illustrated in Figure 10 that shows that the Blija2021 clay has a low erodibility compared to the clay from the Dollardijk. The erodibility coefficient for the different clay covers tested in these physical model tests were estimated in Zwanenburg et al. (2024). It is important to realize that the erodibility coefficient is model dependent, and these coefficients cannot be applied directly in other erosion models.

A method is under development to use small scale soil tests to estimate the erodibility of clay, since it is expensive and time consuming to perform large scale tests in the Delta Flume. The small scale soil tests can be used to estimate the clay characteristics relevant for quantifying the erodibility (Klein Breteler, 2024). When the erodibility of clay can be estimated possibilities arise to use locally available materials in the design, instead of only soil types that fit in the standard erosion categories. Advantages of using local materials are CO2 reduction and ecological benefits. The design formulas also enable innovative designs such as the wide green dike.

CONCLUSIONS

Large scale physical model tests have been performed to study the erosion process of the clay cover with grass on the outer slope under wave attack. The physical model is constructed using an undisturbed layer of clay and grass that is collected from sea dikes using frames by 2 m x 2m wide and 0.8 m deep. Three measurement campaigns have been performed to study the influence of dike geometry and the clay structure on the erosion process.

The physical model tests showed that once the grass cover is damaged, the erosion process of clay consist of two phases. During the first phase, the erosion mainly develops in depth. This erosion process shows a fast increase in erosion depth with a relatively small increase in eroded volume as the additional strength of the grass cover roots in this upper clay layer slows the growth of the erosion hole towards the dike crest. The second phase starts when the erosion depth has progressed to about 50 cm depth: a cliff of clay has formed, where the base of the cliff is eroded by the waves, undermining the layer of clay with grass roots. During the erosion process of this second phase the grass cover roots have negligible influence on the erosion process allowing the erosion hole to grow faster towards the crest.

As a next step, erosion formulas will be derived as input for a probabilistic model that can be used to calculate the required thickness of the clay and the required quality of the grass revetment. These results can be used for the design and safety assessment of coastal flood defences with clay and grass covers. These formulas make it possible to determine the strength of new innovative designs such as the wide green dike. Furthermore, possibilities arise to make use of locally available materials which were considered not suitable according to the traditional clay erosion classes. Advantages of using local materials are CO2 reduction and ecological benefits.

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