EroGRASS
Failure of Grass Cover Layers at Seaward and Shoreward Dike Slopes

- Performance, Results & Conclusions -
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For additional information on the EroGRASS project please visit: www.kyst.dk/erograss.

**Keywords**
Grass cover failure, wave impact, run up and run down flows, wave overtopping, grass sods, prototype dike model, Large Wave Channel.
Summary

Along the North Sea and Baltic Sea coasts, coastal flood defence is mainly performed by dikes, which are mostly covered with grass cover layers that protect the dike core against erosion during storm surges. During storm surges, these grass cover layers are however exposed to hydraulic loading due to wave impact on the outer slope and wave overtopping on the inner slope.

During previous storm surges the grass cover layers often showed large strength and remained undamaged. The clear physical understanding of the erosion of grass cover layers due to different wave loads is, therefore, indispensable today, especially against the background of enhanced hydraulic impact due to climate change.

The main objective of the EroGRASS project was therefore to perform large scale model tests in order to investigate the erosion of the grass cover layer due to (i) wave impact, (ii) wave run-up and run-down flow and (iii) wave overtopping at sea dikes. The large scale tests at a prototype dike model were performed in the Large Wave Flume (GWK) of the Coastal Research Center (a joint centre of the Universities of Hannover and Braunschweig) in Hannover, Germany.

In a first report (Piontkowitz et al., 2009), the design and construction of the dike model in the Large Wave Flume, the measuring and observation techniques and the test programme together with examples of records from the performed tests are described in detail. This second report in hand presents the obtained data, analysis results and conclusions of the EroGRASS experiments.

The EroGRASS experiments showed that wave induced erosion of the grass cover layer can be divided into two independent failure mechanisms:

- Aggregate erosion, initiated due to the crack of the soil by uplift pressures, which are caused underneath the aggregates shortly after wave impact. At the dike surface small aggregates are then lifted and washed away, which eventually results in an erosion hole.

- Block erosion, initiated by impact pressures that penetrate into the soil via large cracks. A horizontal crack is formed at the location of minimum fracture strength. This crack gradually extends until it reaches a critical size and a large block can instantly erosion leaving a large hole in the grass cover.

The tests at the outer dike slope showed that erosion develops sooner at weak locations such as dead plants or bare spots than at locations where the sod is densely rooted. At well rooted locations erosion will mostly not occur, however they can be affected by a weak spot in their vicinity. Weaker spots are therefore more vulnerable to different types of loading and will erode faster.

With respect to aggregate erosion, it can be concluded that erosion rates accelerate with increase in significant wave height. Tests with significant wave heights of 0.7 m caused minor damage, whereas only during tests with significant wave heights of 0.9 m significant damage was inflicted.

As the tests with significant wave heights of 0.9 m were performed at the end of phase 1, the increase of aggregate erosion and significant damage on the outer slope must also be seen in the light of a cumulative degradation of the grass cover layer from test to test. The frequent wave impact intervals during phase 1 implicate an enhanced loading of the grass cover layer on the outer slope that is normally not naturally occurring.
The wave overtopping tests at the inner dike slope showed no damage at the grass cover at all. Even during tests with overtopping volumes between 25 l/sm and 30 l/sm no damage at the inner slope was found. Also at the inner dike foot, where the run down direction of the overtopping volume changes into a horizontal direction and the largest run-down velocity appear, the grass cover stayed undamaged. However, large aggregates were washed over the dike crest. These aggregates originated from the outer slope and indicated that block erosion on the outer slope continued to an increasing degree during phase 2. This underlined the increased degradation and destruction of the grass layer on the outer slope with cumulative wave impact.

Besides damage observations after each test, a green-value method was developed based on video recordings to detect damages in the grass cover. For this purpose, the green value was measured in pre-defined study areas on RGB-images. The green value is defined as an indicator of grass cover condition. The EroGRASS experiments were used to verify the application of the green-value method. The quality of the video recordings was however too poorly due to highly variable lighting conditions, changing camera settings and suboptimal camera locations. Therefore, the method could not been demonstrated and verified. However, recommendations for future studies were made and potential weaknesses of the method were detected.

On the whole, the tests performed in the EroGRASS project showed a high erosion resistance of well-maintained grass cover layers, i.e. the performance of a grass cover layer depends primarily on its management. High erosion resistance is achieved through a close turf with fine and coarse roots. The tests at the outer slope also showed that this high erosion resistance decreases at locations where the grass cover is less maintained and the sod is densely rooted. Weaker spots are therefore more vulnerable to wave loading and erosion. Maintenance of the turf layer is therefore essential for the grass cover strength. The tests showed further, that aggregate erosion and block erosion is dependent on the frequency of loading events. A large number of wave loading events at frequent intervals with few days in between will not give the grass cover enough time to recover after each event. A chain of frequent loading events will therefore provoke degradation of the grass cover layer on dike slopes and, from a certain point of time, increase destruction of the grass cover layer dramatically.
Dansk sammendrag

Langs Nordsøen og Østersøen beskyttes baglandet mod oversvømmelse hovedsageligt af diger, som primært har et græs lag der beskytter digerkernen mod erosion under stormfloder. Under stormfloder udsættes disse græs lag dog for hydraulisk belastning i form af bølgeslag på digets forskråning og bølgeoverløb på digets bagskråning.

Under tidligere stormfloder har græs lagene ofte vist stor styrke og forblev ubeskadiget. Den klare fysiske forståelse af erosionsprocessen ved et græs lag ifølge forskellige bølgepåvirkninger er derfor vigtig i dag, især på baggrund af den fremtidige forøgelse af påvirkningerne som følge af klimaændringerne.

Hovedformålet med EroGRASS projektet var derfor at gennemføre forøget testprogram i form af bølgepåvirkninger på forskråning og bagskråning på digets bagskråning. EroGRASS projektet viser at bølgepåvirkning af græs lag kan opdeles i to uafhængige processer:

- Aggregat erosion, indledte som følge af brud af klæget ifølge økonomisk livliggende åbning og løftes op og vaskes væk fra digets overflade, hvilket i sidste ende kan resultere i et erosionshul i græs laget.
- Blok erosion, initieret af bølgeslagkrafter som trænger ned i klæglaget via store revner. En vandret revne dannes ved stedet hvor klæget har den mindste brudstyrke. En sådan revne udvikler sig gradvist indtil den når en kritisk størrelse og en stor klægblok kan øjeblikkelig eroderer udløbet af overfladen og efterlader et stort hul i græs laget.

Eksperimenterne på digemodellens forskråning viste, at erosion af græs laget udvikler sig hurtigere på svage steder med døde græs planter eller bare pletter end på steder, hvor græs laget er tæt. Ved steder med et tæt rodnet vil erosion af græs laget for det meste ikke forekomme mens forskråningens styrke kan blive påvirket af et svagt punkt i nærheden. Svagere områder i græs laget er derfor mere sårbare over for bølgepåvirkning og vil erodere hurtigere.

Med hensyn til aggregat erosion kan det konkluderes, at erosionsraten forøges med stigende bølgehøjde. Forsøgene med signifikant bølgehøjde på 0,7 m havde mindre skader end for øvriges, mens forsøgene med signifikant bølgehøjde på 0,9 m medførte betydelige skader på forskråningen. Idet forsøgene med signifikant bølgehøjde på 0,9 m blev udført i slutningen af fase 1, må den forøgede aggregat erosion og de betydelig skade på forskråningen også ses i lyset af en kumulativ nedbrydning af græs laget fra forsøg til forsøg. De kurte forsøgssessions med bølgepåvirkning i form af bølgeslag i fase 1 implicerede en øget belastning af græs laget på forskråningen i en sådan grad, som normalt ikke er forekommende i naturen.

Forsøgene med bølgeoverløb viste ingen skader på bagskråningens græs lag. Selv ved forsøgene med overløbsmængder mellem 25 l/sm og 30 l/sm blev der ingen skader registreret på bagskråningen. Det samme gjort sig gældende ved digets indre fod, hvor nedløbsretningen
af overløbsmængden skifter til en horisontal retning og de højeste nedløbshastigheder opnås. Imidlertid blev store aggregater af klæg skyllet over digekronen. Disse klægklumper stammede fra forskråningen og indikerede at blok erosion på forskråningen fortsatte i stigende grad under fase 2. Dette understregede den øgede nedbrydning og ødelæggelse af græslaget på forskråningen ifølge den kumulative bølgepåvirkning.


Forsøgende viste yderligere, at aggregat erosion og blok erosion er afhængig af hyppigheden af bølgepåvirkningerne. Et stort antal hændelser med bølgepåvirkning med korte tidsintervaller (nogle få dage) vil ikke give græslaget tilstrækkelig tid til at reetablerer sig efter hver hændelse. En kæde af hændelser med korte afstande vil derfor fremkalde nedbrydning af græslaget på digernes skråninger og fra et bestemt tidspunkt an vil ødelæggelsen af græslaget stige dramatisk.
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1. Introduction

Protection against coastal flooding is mainly performed by sea dikes along the North Sea and Baltic Sea coasts. These sea dikes are usually protected against erosion by grass cover layers on the seaward and shoreward dike slopes. The grass cover layer is exposed to different forms of wave loading during surges that may provoke failure of the grass cover. Since the failure of the grass cover normally implicates other failure modes which may entail the overall failure of the sea dike, grass cover layers as revetments for flood defence structures have attracted more interest in recent years.

The clear physical understanding of load-resistance processes has become an essential task and grass cover layers are now being considered as a constructional component (EAK, 2002) that has to be designed and managed.

The main intention of the EroGRASS project was therefore to perform large scale model tests in order to investigate the failure of the grass cover layer at sea dikes. The large scale tests at a prototype dike model were performed in the Large Wave Flume (GWK) of the Coastal Research Center (a joint centre of the Universities of Hannover and Braunschweig) in Hannover, Germany. For a detailed description of (i) the design and construction of the dike model, (ii) the measuring and observation techniques and (iii) the test programme, the reader is referred to the first EroGRASS report (Piontkowitz et al., 2009).

1.1 Objectives and methodology

The main objective of the EroGRASS research project was to perform large scale model tests in order to investigate the failure of grass cover layers initiated by

- wave impact due to wave breaking on the seaward slope,
- wave run-up and run-down flow after wave breaking on the seaward slope,
- down-slope flow on the landward slope due to wave overtopping.

Wave impact as well as wave run-up and run-down flow may induce grass cover failure on the seaward dike slope. Wave overtopping may cause failure of the grass cover at the dike crest and on the shoreward slope. Hence, the EroGRASS project dealt with the investigation of grass cover failure along the entire dike profile: seaward slope, dike crest and shoreward slope. The loading by overflow was not considered.

The design, construction and experimental procedure of the large scale model tests were conjointly performed by the FLOODsite Project and the EroGRASS Project. Differences between both projects lie in their scientific focusing: The FLOODsite Project focussed on wave overtopping, the subsequent damage and the breach development initiated from the landward side of the sea dike. The EroGRASS project focussed on the failure of the grass cover layer at sea dike due to different forms of wave impact. The collaboration between the FLOODsite Project and the EroGRASS Project was very useful for the implementation of the most extensive test programme of this kind. Otherwise such a unique enterprise would have been financially and timely hardly affordable. With respect to the scientific research objectives of the FLOODsite Project, the reader is referred to Geisenhainer and Oumeraci (2008).

The report in hand is the second reporting of the EroGRASS project including a description of the performance of the dike model tests, the results and the conclusions concerning the large scale tests. For this, the results and conclusions are based on observations of grass erosion
events during all tests. During the experiments the initiation and progression of grass erosion was registered by photographing and video recordings. The available material has been analysed and conclusive estimations of the erosion of the grass cover have been made.

A second report analysing the experiments carried out in the EroGRASS project was prepared by Mous (2010). His thesis aimed at improving the knowledge of erosion processes on grass-covered seaward dike slopes. For this, he developed an erosion model for grass cover on the outer slope. This erosion model was calibrated and verified by the EroGRASS experiments. For a detailed description of existing grass cover erosion models and the derivation of his erosion model for the prediction of grass erosion on seaward dike slopes, the reader is referred to Mous (2010).

The report in hand is structured as follows: Chapter 2 gives a short review about the prototype dike model built in the Large Wave Flume and the applied test programme. Chapter 3 summarises the most important grass cover layer characteristics and includes a short overview of existing knowledge of erosion processes of grass covers. Chapter 4 deals with the analysis and the results of the tests regarding grass cover erosion due to wave impact on the outer slope of the dike model followed by Chapter 5, that describes the wave overtopping tests and observed grass cover erosion on the inner slope. In Chapter 6 a derived method for analysing grass cover erosion based on a colour range analysis is presented. The report ends with Chapter 7 including conclusions and recommendations.
2. Dike model and test programme

The dike model represents a typical sea dike comparable to typical dike cross sections as usually built in The Netherlands, Germany and Denmark. The slope of the seaward side was chosen to 1:4. This relatively steep slope was chosen instead of 1:6 in order to investigate impact loads due to wave breaking on the seaward slope without the damping effect of the previous wave down rush. The landward slope was 1:3. The height of the dike model was 5.8m and the crest was 2.2m wide (Figure 2.1). No berms were constructed on both slopes. The length of the dike model was 5m, like the width of the flume.

![Cross section of the dike model.](image)

The dike model consisted of a sand core, a clay layer and a grass cover. On both slopes and on the dike crest a clay layer of 0.6m was installed. On top of the clay layer, 0.2m thick grass sands were placed to complete the dike model with a grass cover. By placing the grass sods, the entire clay layer was about 0.8m thick.

In front of the dike model a sloping foreshore was installed to ensure proper conditions for wave transformation (shoaling) in front of the dike model. The slope of the foreshore was 1:40 and the height at the dike toe was 1.0m above the flume bottom. The foreshore length was 40m.

The combined inlet and outlet of the flume is about 35m from the wave paddle. The model was located about 190m from the wave generator due to a window in the flume wall which allowed the observation of the wave impact on the seaward dike slope. The flume area behind the dike model was needed as a reservoir for wave overtopping. For a detailed description of the dike position in the flume, the reader is referred to the first EroGRASS report (Piontkowitz et al., 2009).

The transition between the seaward dike toe and the foreshore is shown in Figure 2.2. The foreshore was built of clay that was connected with the clay layer of the seaward dike slope in order to perform a sealing against infiltrating water.

The toe of the landward slope is stabilised by a concrete corner wall. In front of the concrete wall the clay is build in down to the flume bottom (Figure 2.3). The concrete wall is required to avoid a head cut erosion of the landward dike toe.

With the 0.8m thick clay layer and both construction details A and B, the sand core is completely covered by clay and infiltration into the sand core is reduced. To avoid piping as well as pore pressure and seepage, the dike body was drained. The drainage system was
located on the flume bottom and was emptied by a pump. The phreatic water was pumped into the reservoir behind the dike model.

![Figure 2.2 Detail A - Transition between dike toe and foreshore.](image)

![Figure 2.3 Detail B - Toe protection of the landward slope.](image)

2.1 **Construction of the dike model**

Since a proper scaling of the grass cover layer is not feasible, natural grass was used. The challenge was hereby to get the natural grass into the flume. Since it was not feasible to sow grass on the clay layer and wait for a well-established grass cover, grass sods were excavated from an existing sea dike and transported to the wave flume for installation on the dike model.

The grass sods originated from the flood defence system near Ribe, Denmark (Figure 2.4). The grass sods were excavated with the underlying clay, as it was important that the interaction between the top soil of the grass layer and the underlying clay was not disturbed. The grass cover was of good quality and adequate for investigation of incipient grass cover erosion.

![Figure 2.4 Location of the Ribe defence system and its wing dikes (Denmark).](image)

The complete dike surface to be covered with grass sods was calculated to about 190 m². An area of about 10 m² of grass sods were estimated for substitution of damaged grass areas during testing. In total, about 200 m² of grass sods were therefore excavated. The cross section of an excavated grass sod is shown in Figure 2.5. The excavated grass sods were about...
20cm thick and measured 2.35m in length and 1.25m in width. The weight of one grass sod was approximately 1,100 kg.

Figure 2.5  Cross section of 20cm thick excavated grass sod.

In order to cover the dike model with a 0.8m thick clay layer, an additional clay volume of about 150m³ was needed.

The construction of the dike model including the grass cover took about six weeks. It started with the installation of the foreshore, followed by the sand core and the drainage system. Before installation of the 20cm thick grass mats (grass sods), a 60cm thick clay layer was put on the top of the sand core and compacted. A detailed description of the construction of the entire dike model as well as problems and difficulties encountered during the construction phase are given in the following sections.

2.1.1 Sand core and the foreland

The construction of the dike model started with installation of the foreshore. The compaction density was measured during construction. The compaction ranged from 1.52 to 1.612t/m³ with a moisture content of about 22.0% and 22.8%. The applied foreshore clay (Type A) was different to the clay (Type B) which was used for the clay layer at the dike model. The clay for the foreshore (Type A) was available at the Large Wave Flume. The soil characteristics are further described in the first EroGRASS report (Piontkowitz et al., 2009). The completed foreshore is shown in Figure 2.9. The toe of the foreshore was protected against erosion by three 1.33m long and 40cm high concrete blocks (Figure 2.6). After installation of the foreshore, the lower part of the sand core was heaped up. However, before installing the sand core, the required drainage system was installed. The system consisted of three pipes (diameter of 20cm) wrapped with coco fibres (Figure 2.7). All three pipes ran into a well that was placed on the landward side of the dike model.
The well consisted of three prefabricated concrete rings and was caulked against water intrusion from outside (Figure 2.8).

The sand of the dike core was transported by a wheel loader (Figure 2.10) from the sand storage into the flume. The sand storage was located on the same yard as the flume. The sand was installed in layers of 50 cm thickness (Figure 2.11), and afterwards compacted by a plate compactor. The foreshore as well as the sand core was compacted alongside the flume walls with a pneumatic rammer to assure a good contact between the soil and the concrete walls. Due to only one entrance into the flume, installation of the clay layer on the seaward slope was performed simultaneously during installing the upper sand core layers (Figure 2.12).
2.1.2 Clay layer

The clay material for the dike model originates from a clay pit near Ribe, Denmark. The clay was transported by trucks from Denmark to Hannover and stored uncovered for a short time on the yard of the Coastal Research Centre (Figure 2.14).

The clay was transported by the wheel loader into the flume. First the lower part of the clay layer on the seaward slope was installed (Figure 2.15). The 60cm thick clay layer was built in two steps, installing a 30cm thick layer each time with subsequent compaction of the clay material. After completion of the seaward clay layer and the sand core, the clay layer on the landward slope as well as on the crest was built in (Figure 2.16). Clay compaction of the first 30cm thick clay layer was performed by a loader (Figure 2.17). Compaction of the second 30cm thick clay layer was carried out by using a rammer and a small roll (Figure 2.18).
2.1.3 Grass sods (excavation and installation)

Excavation

During the last week of January 2008, the grass sods were excavated from the dike crest of the Ribe flood defence system in Denmark. The excavation of the 80 grass sods lasted 3 days. First, a tractor with a horizontal blade and two smaller vertical blades cut the connection between the future grass sod and the surrounding soil and grass (Figure 2.19). While pulling the attachment, a wooden plate connected to the attachment by two chains was pulled underneath the grass sod at the same time.
After the wooden plate was pulled under the grass sod, the cutting process was stopped and the fork of a fork lifter was pushed under the wooden plate to lift up the grass sod on the plate (Figure 2.20). Afterwards the grass sod edges were cut straight by hand (Figure 2.21). Four square timbers were installed under the plate (Figure 2.23) and a wooden frame was built around the grass sod to avoid any damage or the appearances of additional fissures (Figure 2.24). All 80 grass sods were stored on the field close to the wing dike for 1-3 days before they were transported to Hannover (Figure 2.22).
Installation

After the grass mats were unloaded from the trucks in Hannover (Figure 2.25) by a fork lifter, the 80 grass sods were temporarily stored outside the Large Wave Flume (Figure 2.26) to allow for continued natural growth with natural light and weather conditions. The disadvantage of doing so was an increase of the moisture content of the soil due to possible precipitation. In order to avoid this, the grass sods were covered with a plastic cover in case of rainfall or snowfall forecast.

The square timbers and the wooden frame were removed before installation of the grass sods. Each grass sod was placed with the fork lifter on a wooden framework (Figure 2.27 and Figure 2.28) which allowed an easier preparation of the sods for installation. Two holes were drilled into the underlying wooden plate which was needed for the later removal of the plate under the grass sod.

To avoid longitudinal joints running all way up both dike slopes, it was decided to install the grass sods in displaced order. The grass sods were installed transverse to the flume and in rows. One row consisted of three grass sods with lengths of 0.9m, 2.35m and 1.45m. These three lengths covered the entire width of the flume (5m). The row positions of the grass sods with lengths of 0.9m and 1.45m were switched in every row. The 2.35m long grass sod always remained as the central grass sod. By that, longitudinal joints running non-stop up both slopes were avoided (Figure 2.29).
In order to get grass sods of 0.9m and 1.45m length, a number of 2.35m long grass sods had to be cut. First the underlying wooden plate was cut using a circle saw and then the grass sod was cut with a steel wire. For transportation of the grass sods from the entrance of the Large Wave Flume to the dike model, a steel beam and a wooden transport frame were used which made it possible to hook the grass sod to the crane runway (Figure 2.30). The wooden transport frame was installed between the steel beam and grass sod to avoid the tilting of the grass sod during transport (Figure 2.31). The steel beam was braced to the grass sod and the wooden transport frame by synthetic ropes (Figure 2.32). Three different steel beams and two different wooden frames were used in order to handle the three different sizes of grass sods. At both holes which before were drilled into the plate, hooks were installed (Figure 2.34). These hooks were designed for pulling the wooden plates underneath the grass sod after being placed on the dike slope.

Figure 2.29  Displaced order on the seaward dike slope.

Figure 2.30  Transport of grass sods by the crane runway.

Figure 2.31  Wooden transport frame, steel hooks and two steel beams.

Figure 2.32  Bracing a grass sod to the transport frame and the steel beam with synthetic ropes.
At the dike model, the grass sod was placed at its installation position (Figure 2.33) and the wooden transport frame, steel beam and synthetic ropes were removed. After one row of grass sods was completed, the steel hooks (Figure 2.34) were connected to a second set of synthetic ropes (blue ropes in Figure 2.35). Next, a wooden beam (5m long) was installed above the row of grass sods (Figure 2.36) by fixing it between the flume walls using wooden wedges. The function of the wooden beam was to provide a bearing during the process of removing the wooden plates under the grass sods.

The crane runway of the Large Wave Flume was used for pulling the wooden plates underneath the grass sods. The synthetic ropes were connected to a steel cable (Figure 2.37) which again was hooked to the crane hook. The steel cable was led over a deflexion pulley to avoid a lean traction as the crane hook only moves in vertical direction. The deflexion pulley was fixed to a steal beam, which was placed across the flume (Figure 2.38).

![Figure 2.33 Installation of the third grass sod of a row.](image)

![Figure 2.34 Steel hook.](image)

![Figure 2.35 Installed grass sods including the underlying wooden plate and the steel hooks.](image)

![Figure 2.36 Wooden beam fixed between both flume walls.](image)
First, the wooden plate under the 2.35m long grass sod was removed followed by the two smaller grass sods (Figure 2.39). After installation of the grass sods, all gaps and joints between the sods and the concrete flume walls were closed with clay. The clay, which was filled into the joints, was compacted by hand. The installation of the grass sods was started at the toe of the seaward slope and continued up to the dike crest. Afterwards the grass sods on the landward slope were installed, again starting at the dike toe. Finally, grass sods were installed at the dike crest whereby the grass cover was closed (Figure 2.40). After installation of the entire grass cover, all gaps and joints were again checked, especially the joints along the flume walls.

In order to strengthen the connection between the grass sods and the underlying clay layer, the grass sods were compacted. After a few trials on the seaward slope, local damages of the grass cover were observed and the compaction of the grass sods was stopped. A damaged area can be seen in Figure 2.41.
Artificial lightning of the grass sods was installed since the light quantity inside the Large Wave Flume was not enough to support grass growth. Special lamps for plant growth were used for illumination. In addition to the artificial lightning, the grass sods were irrigated four times in the period between installation and testing. The first EroGRASS report (Piontkowitz et al., 2009) includes a detailed description of the positioning of the artificial illumination sets and the maintenance of the grass layer before testing.

2.1.4 Problems and difficulties

During construction of the dike model a number of problems had to be solved and managed. In the following, these problems and the lessons learned by solving these are described.

- The approach used for grass sod installation resulted in a partly uneven and rough surface of the seaward and shoreward slope. The attempt to compact the grass sods resulted in local damages of the grass layer. However, the surface can be made more even by using grass sods with the same thickness. It is, though, difficult to go for a constant thickness of each grass sod as the grass layer of a ‘real’ sea dike is a natural product. The method of excavating the grass sods at the Ribe dike showed that cutting the grass sods in horizontal direction is difficult but not impractical. Weather conditions during excavation of the grass sods were very poor. Less precipitation the days before excavation and a more advanced method to control the cutting depth will result in a more constant thickness of the grass sods.

- The approach used for installation of the grass sods has to be improved in the future. The method used implied that every grass sod had to be handled very carefully to avoid additional cracks and fissures. This again was very time-consuming and asked for much strenuous manual work. Tools, such as hydraulic shields, should be developed to reduce the amount of manual work. The disposability of only one crane...
in the Large Wave Flume turned out to be also time-consuming as the one crane was used for many operations which again resulted in a number of re-settings of the crane.

- On the seaward side a couple of buckles could be observed. These buckles were caused by pulling the wooden plates underneath the grass sods and pressing the grass sod at the same time against the wooden beam, which functioned as a bearing during the process of removing the wooden plates under the grass sods. An improved method of installing the grass sods on both dike slopes will solve this problem.

- The lightening of the grass layer was important and enabled the grass layer to grow satisfactorily. The aeration of grass layer could be useful to dry the surface and remove the moisture between the grass leaves.

- Another problem caused by the uneven seaward slope surface was the influence of grass mat edges on the stability of the complete grass mat. In some cases, a small step between the lower and the following upper grass mat could be noticed. These steps were however loaded by wave run-up.
3. Review of grass cover layer characteristics

The interest in grass as cover layers for dikes has been growing in recent years because it is a cheap and sustainable dike protection, whose strength has been underestimated. This section gives a short overview of existing knowledge of the typical composition of a grass cover, which also includes a description of the characteristics of clay. Subsequently the state of knowledge of erosion processes of grass covers is given.

3.1 Structure of the grass cover layer

The turf is the root mat which provides the strength and erosion resistance to the clay layer. The roots penetrate the clay layer causing a soil structure of cracks and aggregates, but at the same time they keep the soil particles together and create a flexible and tough layer that offers significantly higher erosion resistance than a bare clay layer (Young, 2005). Model tests by Möller et al. (2002) showed that as soon as water is flowing over a clay surface, gulley formation will start rapidly.

Investigations carried out by Springers (1999) show that the performance of a grass cover layer depends primarily on its management. The ideal grassland is unfertilised, periodically grazed and rich of species. This form of management provokes a closed turf with fine and coarse roots. This network of fine and coarse roots makes the top soil a strong and flexible layer that can deform without tearing (TAW, 1997). Conversely, the underlying subsoil (clay layer) is stiff (or plastic when moist or not yet aged) and usually somewhat less permeable. The erosion resistance of the top soil near the surface is (usually) higher than at deeper parts of this layer. The upper, densely rooted part, with an irregular bed structure and a higher erosion resistance, is called sod. A sod with a thick network of roots and grass coverage of more than 70-85% has a good erosion resistance. 65% of the grass roots are located in the upper soil layer (0-6cm depth). Between 6cm and 15cm 20% of the roots can be found. The
remaining percentage of roots is located in a depth up to 50 cm (Sprangers, 1999). According to TAW (1997), three zones of the grass sod can be identified having different erosion resistance and characteristics:

- **Stubble**: consists of loose soil and plant remains, which are washed away by run-up and run-down flow relatively quickly. It is therefore assumed to have no strength obtained from clay or root cohesion.

- **Turf**: is placed directly below the stubble and has a high root density. The strength is given by the cohesion of the clay aggregates and the root cohesion, but as depth increases the root cohesion diminishes.

- **Substrate**: consists of mostly clay and few roots. The strength is provided by the clay cohesion and the effect of compaction.

Referring to the overtopping tests on a poorly developed grass cover at a Groningen sea dike (Delfzijl) (Akkerman et al. 2007), Mous (2010) notes that the synergy of the root system and the clay may be an important factor for the erosion resistance of the total grass cover. The tests showed some compensating effect between the poor root network and the clay quality. Despite the poorly developed root system, the clay quality was rather good. It was therefore concluded vice versa, that a well developed root system may have a negative influence on the clay quality.

One factor of synergy may be the moisture content. The moisture content changes leading to shrinkage and shear cracks in the clay. The change of the moisture content is due to the plant extraction of water from the clay.

The degree of prevention of high velocities and stresses at the soil-water interface of vegetal cover is described by the vegetal cover factor $C_F$, see Temple et al. (1987). The cover factor is dominated by the density and uniformity of density in the immediate vicinity of the soil boundary. In Table 3.1 generalised vegetal cover factors are shown. These do not depend on the species of the vegetal cover.

**Table 3.1 Vegetal cover factor by Temple & Hanson (1994).**

<table>
<thead>
<tr>
<th>Cover description</th>
<th>Vegetal cover factor $C_F$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Good vegetal cover</td>
<td>0.75</td>
</tr>
<tr>
<td>Fair vegetal cover</td>
<td>0.50</td>
</tr>
<tr>
<td>Poor vegetal cover</td>
<td>0.25</td>
</tr>
</tbody>
</table>

**Clay**

Clay consists of fine particles for the major part and is defined as cohesive soil. It has the ability to retain water due to the fact water molecules attach to the surface of the soil particles with relative ease. Also the small pores have a large resistance preventing the transport of water through the clay. Therefore, clay normally has a low permeability, especially shortly after application. However, after some time the permeability increased significantly due to the penetration of roots and holes and cracks caused by the burrowing of animals (Table 3.2).
When assessing the erosion resistance of clay it is important to consider, that the characteristics of the clay layer will constantly change. Clay will shrink and swell in response to changes in moisture content, so generating shrinkage and shear cracks. The formation of shrinkage cracks or fissures can be up to 125mm deep (Coppin and Richards, 1990; after Anderson et al, 1982) in clay, and sometimes increase in width below the upper heavily rooted soil layer. These structures in the soil can be evident 0.8m below the surface (TAW, 1996), and is very marked within the top rooted layer. Root development follows and exploits cracks. Worm holes and burrowing animals have similar effect. There will be preferential weathering of the soil along the cracks, so accentuating the appearance of soil aggregates in the turf.

The erosion resistance of clay can be categorised by the water content and the sand content. According to TAW (1996), clay is classified into three erosion resistant categories, see Table 3.3. According to EAK (2002), clay that is used for sea dike revetments should also meet the requirements specified in Table 3.4.

### Table 3.2 Hydraulic permeability of clay (TAW, 1996).

<table>
<thead>
<tr>
<th>Condition of the clay</th>
<th>Hydraulic permeability [m/s]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Directly after construction</td>
<td>$10^{-6}$</td>
</tr>
<tr>
<td>Fine soil structure</td>
<td>$10^{-5}$</td>
</tr>
<tr>
<td>Large cracks and animal tunnels</td>
<td>$10^{-4}$</td>
</tr>
</tbody>
</table>

### Table 3.3 Classification of clay erosion resistance (TAW, 1996).

<table>
<thead>
<tr>
<th>Clay category</th>
<th>Water content $w$ [%]</th>
<th>Plasticity Index $\cdot$ (w - 20)</th>
<th>Sand content [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Erosion resistant</td>
<td>&gt; 45</td>
<td>&gt; 0.73</td>
<td>&lt; 40</td>
</tr>
<tr>
<td>Moderate erosion resistance</td>
<td>&lt; 45</td>
<td>&gt; 18</td>
<td>&lt; 40</td>
</tr>
<tr>
<td>Low erosion resistance</td>
<td>&lt; 45</td>
<td>&lt; 18</td>
<td>&lt; 40</td>
</tr>
</tbody>
</table>

### Table 3.4 Requirements for clay used as dike revetment (EAK, 2002).

<table>
<thead>
<tr>
<th>Soil property</th>
<th>Threshold</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sand content $(d &gt; 0.06,\text{mm})$</td>
<td>&lt; 40%</td>
</tr>
<tr>
<td>Clay content $(d &lt; 0.002,\text{mm})$</td>
<td>&gt; 10%</td>
</tr>
<tr>
<td>Liquidity Limit</td>
<td>$w_L &gt; 25%$</td>
</tr>
<tr>
<td>Plasticity Limit</td>
<td>$w_P &gt; 15%$</td>
</tr>
<tr>
<td>Undrained Shear Strength</td>
<td>&gt; 20 KN/m$^2$</td>
</tr>
<tr>
<td>Dry density</td>
<td>$0.85 &lt; \rho_d &lt; 1.45 , \text{t/m}^3$</td>
</tr>
<tr>
<td>Water content</td>
<td>$80% &gt; w &gt; 30%$</td>
</tr>
</tbody>
</table>
Clay will shrink and swell in response to changes in moisture content, so generating shrinkage and shear cracks. Soil cracking increases soil permeability and infiltration. Plant extraction of water from clay soils leads to desiccation and the formation of shrinkage cracks or fissures. These can be up to 125mm deep (Coppin and Richards, 1990; after Anderson et al, 1982) in clay, and sometimes increase in width below the upper heavily rooted soil layer. Soil structure can be evident 0.8m below the surface (TAW, 1996), and is very marked within the top rooted layer. Root development follows and exploits cracks. Worm holes and burrowing animals have similar effect. There will be preferential weathering of the soil along the cracks, so accentuating the appearance of soil aggregates in the turf.

3.2 Erosion process

There has to be distinguished between the erosion of grass covers and the erosion of bare clay as the grass provides additional strength. The density of the root system and the covering rate influence the erosion rate. Due to the variability of the grass cover layer, bare spots without grass coverage can limit the strength of a grassed dike slope.

Based on the results of Delft Cluster (2002, source: Mous, 2010), the following parameters were defined amongst others influencing the stability of the clay: soil structure, density, percentage clay/sand, salinity of the ground and the water, humidity of the ground, clay mineral structure, Na+ density, organic material, temperature.

The Dutch VTV 2006 (source: Mous, 2010) distinguishes six failure mechanisms in which separately or in combination the entire erosion of the grass cover layer can occur:

- Washing away of small soil particles and small slumps from the roots. If this leads to gradual erosion concerning a large surface, then generally this is not considered as damage. This mechanism can however also lead to such ground displacements that the cover layer becomes uneven or vegetation is disturbed.
- Sudden washing away of large aggregates as a result of water pressure differences between the cavities and cracks in the substrate and the outside water. Inconsistencies in the covering layer enhance these pressure differences.
- Breaking up of the sod due to strong local erosion;
- Breaking up the sod by wave impact or currents when a large hole is present in the vicinity.
- Erosion of clay substrate after the grass sod has disappeared (the residual strength);
- Sliding of the grass sod along a shear plane through the substrate as a result of saturation of the soil and groundwater flow.

With respect to the first four erosion mechanisms, they represent failure due to wave impact, wave run-up and run-down flow and wave overtopping. Referring to the first erosion mechanism of the washing away of small particles, Mous (2010) overall classifies this failure as aggregate erosion, whereas the second erosion mechanism (sudden failure of large aggregates due to water pressure differences) is classified as block erosion.

These mechanisms can be triggered during wave impact or by flowing run-up and run-down water. Mous (2010) lists several processes that can cause erosion during the wave impact (Figure 4-3):
- Direct hit of shock pressures;
- Splash water around the impact area that can erode the surface with very high velocity;
- Wave run-up and run-down velocities that continuously cause erosion over the surface;
- Uplift forces during wave run-down.

**Figure 3.2** Water flow and movement of the soil during wave attack (TAW, 1997).

The wave impact pressure caused by the falling water produces a compression of the soil (Figure 3.3). This compression leads to horizontal deformation of the adjacent soil of the cover layer. The soil is thus deformed in the horizontal plane by tensile forces. This deformation can locally result in cracks in the cover layer. It is assumed, however, that in rooted soils the hazard of inducing cracks due to wave impact is smaller compared to a clay layer without grass roots (Mouns, 2010).

**Figure 3.3** Impact causing horizontal deformation (left) and local failure (Mous, 2010).

As fissuring of the clay continues the permeability of the sod is increased. Simultaneously the clay pores and the macro pores in between the soil aggregates are gradually filled with water until the soil is saturated. The soil strength is gradually weakened while its water content increases.

When the top layer of the sod is very permeable due to soil structure and small cracks, the breaking wave impacts can even be in direct contact with the pore water (Figure 3.4 left). The impact pressure can then be transmitted to the pore water and because water has
universal pressure distribution, pressures in upwards direction can be generated temporarily underneath a soil aggregate (Figure 3.4 right). The splashing water also exerts a force on these particles which can wash away the uplifted aggregates. Already loose small particles can be lifted up and eroded washed, but also particles supported by a root can erode when they are pulled off their roots or when these roots break or are pulled out.

The erosion of small particles increases permeability even more, and the sod can become spongy, which amplifies all of the processes described above. This was also observed during overtopping test in the field (Bakker, Mom et al. 2008) where a permeability increase eventually led to the balloon mechanism, which occurred in a later stage; a bulge was formed on the inner slope which gradually increased in size.

Figure 3.4 Wave impact in direct contact with pore water (left) results in upward pressure (right) (Mous, 2010).

Besides the removal of smaller pieces, which forms a scour hole, also block erosion can occur. Before the scour hole has reached the subsoil the total sod is then lifted up after a wave impact. Cracks and cavities in the scour hole are deformed and enlarged due to the persistent wave impacts and the erosion of small pieces. The turf becomes spongier and at a certain moment shrinkage cracks that were already present in the deeper part of the cover layer are opened up or smaller cracks widen due to the deformation of their side walls by subsequent impacts. This allows the water and the impact load to reach deeper parts of the grass cover (Figure 3.5).

Figure 3.5 Crack opened up after aggregate erosion (left), pressure dispersion in the upper soil (right) (Mous, 2010).
In the case of water-filled cracks, the wave impact can cause an explosive effect in the upper soil that plays a major part in the erosion process. Due to the fact that the clay is relatively impermeable, the crack causes a local permeability where the impact pressure causes uplift forces around large aggregates in the sod. Shortly after the wave impact pressure at the surface has diminished, a high pressure is still present in the crack (Mous, 2010).

Dike slope locations with less root development are normally more vulnerable to block erosion than areas with a well-rooted grass layer. Small and thin roots can be broken or pulled out of the saturated clay by the uplift pressure in the crack.
4. Test results: Wave impact

The test programme was divided into two phases. The first phase comprised tests regarding the initiation of grass erosion on the seaward slope due to wave impact, whereas the second phase dealt with the initiation of grass erosion on the landward slope due to wave overtopping. For both slopes, the focus is on observed damage of the turf layer as it is the toughest part of the grass cover. In case of erosion of this highly resistant layer, the erosion rate at either the outer or inner slope will dramatically increase and the damage will grow without later containment.

Observed damage is defined as the moment when grass erosion triggers ongoing damage of the upper part of the turf. According to Mous (2010), this ongoing damage can be defined as a critical erosion depth causing a decrease of the strength of the covering grass layer. The critical erosion depth must correspond to the underside of the highly resistant turf layer and can therefore be estimated to be at a depth of 5-7 cm. Furthermore, this critical erosion depth can also be related to a critical root density or critical root depth (Mous, 2010). The critical erosion depth, however, can be reached either by aggregate erosion or by instant block erosion. The analysis of observed damage of the turf layer will therefore consider both initiation mechanisms of grass erosion.

In the following sections, the tests regarding grass cover erosion due to wave impact are presented: Section 4.1 gives short overview of the test program during phase 1 and lists the hydraulic parameters as well as the performed tests. Section 4.2 summarises the analysis of the test data performed by Mous (2010). Section 4.3 includes the description of observed grass erosion and damage on the outer slope according to both erosion mechanisms: aggregate erosion and block erosion.

4.1 Test program

The applied wave spectra was based on a TMA spectrum, which is a modified JONSWAP spectrum accounting for limited water depth. The water level in the flume was kept constant during test phase 1 and test phase 2. The effect of a tide could not be simulated in the flume. Table 4.1 gives an overview of the hydraulic parameters of each test run, i.e. peak period $T_p$, the significant wave height $H_s$ and the water depth $d$.

<table>
<thead>
<tr>
<th>Hydraulic Parameter</th>
<th>April 8 / 16</th>
<th>April 18 / 22</th>
<th>April 8 / 10</th>
<th>April 11 / 22</th>
</tr>
</thead>
<tbody>
<tr>
<td>$T_p$ [s]</td>
<td>4.0</td>
<td>5.0</td>
<td>5.0</td>
<td>5.0</td>
</tr>
<tr>
<td>$H_s$ [m]</td>
<td>0.5</td>
<td>0.7</td>
<td>0.8</td>
<td>0.9</td>
</tr>
<tr>
<td>$d$ [m]</td>
<td>3.7</td>
<td>3.7</td>
<td>3.7</td>
<td>3.7</td>
</tr>
<tr>
<td>No. of tests</td>
<td>4</td>
<td>3</td>
<td>2</td>
<td>4</td>
</tr>
<tr>
<td>Performed tests</td>
<td>April 8 test 1, April 16 test 1</td>
<td>April 18 test 1, April 18 test 2, April 16 test 3</td>
<td>April 8 test 2, April 10 test 1</td>
<td>April 11 test 1, April 22 test 2, April 22 test 3</td>
</tr>
</tbody>
</table>

After each test the Large Wave Flume was emptied for water which lasted 4 hours. Filling the flume took 5 hours. Consequently, testing was normally interrupted by one day without testing. After each test run the damage of the grass cover was surveyed and documented by
photos. When the grass cover was damaged, the grass sod concerned was replaced by a new grass sod.

4.2 Analysis of data

In order to analyse and evaluate the observed initiation of grass erosion on the seaward slope due to wave impact, an analysis of the measured wave and pressure data was performed by Mous (2010).

4.2.1 Wave analysis

A wave analysis for each test has been carried out in order to verify that the intended wave characteristics during each test were actually observed in terms of the incoming waves. Furthermore, Mous (2010) performed a reflection analysis of the incoming waves. The results are shown in Table 4.2.

Table 4.2 Wave characteristics of incident and reflected waves after reflection analysis (Mous, 2010).

<table>
<thead>
<tr>
<th>Test</th>
<th>Incident</th>
<th>Reflected</th>
</tr>
</thead>
<tbody>
<tr>
<td>8 April test 2</td>
<td>0.8 m / 5.0 s</td>
<td>0.531</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0.763</td>
</tr>
<tr>
<td>10 April test 1</td>
<td>0.8 m / 5.0 s</td>
<td>0.551</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0.785</td>
</tr>
<tr>
<td>11 April test 1</td>
<td>0.9 m / 5.0 s</td>
<td>0.621</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0.857</td>
</tr>
<tr>
<td>16 April test 1</td>
<td>0.5 m / 4.0 s</td>
<td>0.339</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0.484</td>
</tr>
<tr>
<td>16 April test 2</td>
<td>0.5 m / 4.0 s</td>
<td>0.337</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0.484</td>
</tr>
<tr>
<td>16 April test 3</td>
<td>0.5 m / 4.0 s</td>
<td>0.338</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0.485</td>
</tr>
<tr>
<td>22 April test 1</td>
<td>0.7 m / 5.0 s</td>
<td>0.481</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0.676</td>
</tr>
<tr>
<td>22 April test 2</td>
<td>0.9 m / 5.0 s</td>
<td>0.585</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0.837</td>
</tr>
<tr>
<td>22 April test 3</td>
<td>0.9 m / 5.0 s</td>
<td>0.381</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0.849</td>
</tr>
</tbody>
</table>

Most tests have a reasonably good agreement with the desired wave heights; the difference is within 0.05 m. Only the tests on April 22 have a slightly larger difference between the intended wave height and the observed wave height.

4.2.2 Pressure data analysis

Mous (2010) performed a statistical analysis on the pressure records of all available tests. All pressure records were examined in L-DAVIS and per wave period one maximum pressure was identified. This method was chosen by Mous (2010) in order not to identify all input pressures as automatically impact pressures. Hence, the troublesome task of identifying every single wave impact pressure peak for each test was avoided. The disadvantage of this method, however, is that quasi static water pressures are included in the input. But as these are rather low, they will most probably not initiate significant erosion (Mous, 2010). Maximum

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1 L-Davis (LWI Data Analysis and Visualisation Software) is special software developed by the Leichtweiß Institute of the Technical University of Braunschweig. The software can be used to analyse data of different measuring devices that are used in the Large Wave Channel in Hannover.
pressures, which occurred during no wave loading, were therefore excluded from the data analysis.

The analysis of the pressure data resulted in maximum pressures either occurring at pressure transducer PT2 (DMD 2) or at pressure transducer PT3 (DMD 3) during all tests. Hence the data analysis has been limited to the pressure transducer PT2 and PT3.

**Table 4.3 Statistical analysis of the pressure data (after Mous, 2010).**

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>8 April test 2</td>
<td>DMD 2</td>
<td>394</td>
<td>3.49</td>
<td>16.01</td>
<td>2.93</td>
<td>3.97</td>
<td>6.73</td>
<td>9.75</td>
<td>12.33</td>
</tr>
<tr>
<td>10 April test 1</td>
<td>DMD 2</td>
<td>836</td>
<td>3.34</td>
<td>18.76</td>
<td>2.96</td>
<td>3.90</td>
<td>5.93</td>
<td>7.78</td>
<td>12.77</td>
</tr>
<tr>
<td>11 April test 1</td>
<td>DMD 2, DMD 3</td>
<td>483, 517</td>
<td>4.41, 3.70</td>
<td>20.32, 12.95</td>
<td>4.01, 3.70</td>
<td>4.91, 3.85</td>
<td>7.04, 4.29</td>
<td>10.43, 5.98</td>
<td>15.35, 9.89</td>
</tr>
<tr>
<td>16 April test 1</td>
<td>DMD 3</td>
<td>1035</td>
<td>2.94</td>
<td>12.95</td>
<td>3.05</td>
<td>3.33</td>
<td>3.82</td>
<td>6.37</td>
<td>8.70</td>
</tr>
<tr>
<td>16 April test 2</td>
<td>DMD 3</td>
<td>1123</td>
<td>2.96</td>
<td>33.79</td>
<td>2.06</td>
<td>2.57</td>
<td>5.07</td>
<td>13.12</td>
<td>22.24</td>
</tr>
<tr>
<td>16 April test 3</td>
<td>DMD 3</td>
<td>1038</td>
<td>3.04</td>
<td>18.89</td>
<td>3.13</td>
<td>3.45</td>
<td>4.08</td>
<td>6.44</td>
<td>11.26</td>
</tr>
<tr>
<td>22 April test 2</td>
<td>DMD 3</td>
<td>843</td>
<td>4.53</td>
<td>33.79</td>
<td>3.78</td>
<td>4.61</td>
<td>7.38</td>
<td>13.74</td>
<td>25.25</td>
</tr>
<tr>
<td>22 April test 3</td>
<td>DMD 3</td>
<td>147</td>
<td>4.47</td>
<td>18.89</td>
<td>4.02</td>
<td>4.70</td>
<td>7.29</td>
<td>12.00</td>
<td>15.69</td>
</tr>
</tbody>
</table>

The statistical analysis of the tests 8 April test 2 and 10 April test 1 are in well agreement and it is concluded that the conditions during both tests were equal, since the hydraulic parameters of both tests were the same ($H_s = 0.8 \text{ m}$, $T_p = 5.0 \text{ s}$).

The tests 11 April test 1, 22 April test 2 and 22 April test 3 were carried out with $H_s = 0.90 \text{ m}$ and $T_p = 5.0 \text{ s}$. Since the hydraulic parameters of all tests were the same, it was expected that the highest pressures during all of these tests would occur at the same pressure transducer (DMD 3). However, from the pressure records of the test 11 April test 1 it appeared that highest pressures occurred at DMD 2, implicating the consideration of the pressure transducer DMD 2 in the statistical analysis.

Unfortunately, test 22 April test 3 was of very short duration since only 147 maxima were measured. Furthermore, the maximum values of test 11 April (DMD 3) differ significantly from the maximum pressures of test 22 April (DMD 3) despite same hydraulic parameters. This, together with the fact that the maximum pressures occurred at the different location DMD 2 on April 11 compared to the maximum pressure data of April 22 at DMD 3, indicates some error of mistake with the data of April 11 (Mous, 2010).

All tests on April 16 were performed with the same hydraulic parameters ($H_s = 0.5 \text{ m}$, $T_p = 4.0 \text{ s}$). By comparing the statistical analysis of test 1 and test 3 on April 16, a very good agreement between both tests can be seen. Contrary to this test 2 have significantly higher extreme values. Mous (2010) makes note of that this difference cannot be directly explained due to the fact that all tests on April 16 have approximately the same number of samples. This gives reason to question the correctness of the data recorded during test 2 on April 16 (Mous, 2010).
4.3 Damage observations
The survey for damage of the grass cover after each test run had the objective to describe
- the instantaneous damage caused by single breaking wave impact events and
- the damage over the entire duration of the test.

4.3.1 Damage by single wave impact events
The first damage of the grass cover occurred closed to the observation window in the flume
wall during the tests on April 11th, 2008. The wave parameters were $T_p = 5.0s$ and $H_S = 0.9m$.
The water depth was about 3.7m. The damage was caused by a single wave impact. As shown
in Figure 4.2, only a portion of the 90cm wide grass sod was damaged. The original stage of
the grass sod is shown in Figure 4.1. The dimension of the damaged area is illustrated in
Figure 4.3. However, the marked area A in Figure 4.3 shows an area of the grass sod that was
not eroded directly in front of the observation window. After investigation of the soil surface
of the damaged grass sod, it was noticed that the visible clay was not part of the clay layer
underneath the grass sod, rather the clay of the grass cover as the hole was just 10cm deep
(Figure 4.4).

![Figure 4.1](image1.png) **Figure 4.1** Undamaged grass sod in front of
the observation window (before wave impact).

![Figure 4.2](image2.png) **Figure 4.2** First damage on the observation
window (after wave impact).

![Figure 4.3](image3.png) **Figure 4.3** Dimensions of hole in the grass cover (max. scour depth ~10cm).
In order to repair the grass cover layer, the remaining grass sod (area A, Figure 4.3) and the underlying clay were removed. Moreover, the hole was enlarged where with the new grass sod piece for repair sized 53cm in width and 70cm in length (Figure 4.5 and Figure 4.6). The repaired grass sod can be seen in Figure 4.7.

4.3.2 Damage over entire test duration

During the entire test duration, different kinds of damage or stages of damage were observed. Round aggregates of different size were observed on the dike surface (Figure 4.8) and within the topsoil. It is, however, important to notice that the development of these round aggregates was not the result of lose clay lumps being moved up and down the slope. These aggregates were also observed in the soil with a dense root network (Figure 4.9).

In some cases, the clay material which was used to close the joints between the grass sods was removed and had to be replaced. Moreover, small holes (Figure 4.10) were registered after the tests.

The degradation of the grass layer in the surf zone caused by both test periods (phase 1 and phase 2) is shown in Figure 4.11. The grass cover (swords and leafs) in the lower part of the seaward slope remained green and alive longer than the grass within the breaker zone. The grass cover that was permanently inundated was much less degraded than the grass cover in the breaker zone that turned into a more brownish colour. After three days without testing, new small grass leafs were noticed.
During the wave overtopping tests (test phase 2), the seaward grass cover was continually damaged. Due to the increased water level, the breaker zone moved upwards whereby the damaged grass sods were found in row K (Figure 4.12). Furthermore, damaged joints between grass sods on the seaward slope were registered (Figure 4.13).
4.4 Aggregated erosion and block erosion during the tests

In order to get a more detailed overview of events of aggregated erosion and block erosion, the available photographs and video recordings have been studied and changes in the dike surface and grass layer have been gathered and analysed after each test (cp. Table 4.4). The location of the rows to identify damage on the seaward dike slope and the position of the pressure transducers is shown in Figure 4.16.

Table 4.4 Overview of erosion events during the first test phase (after Mous, 2010).

<table>
<thead>
<tr>
<th>Test</th>
<th>H_s [m] / T_p [s] / Load duration [s]</th>
<th>Accumulated load duration</th>
<th>Type of erosion</th>
<th>Location</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>8 April test 1</td>
<td>0.5 m / 4.0 s</td>
<td></td>
<td>No visible erosion</td>
<td></td>
<td></td>
</tr>
<tr>
<td>8 April test 2</td>
<td>0.8 m / 5.0 s / 1800 s</td>
<td>1800 s (30 min)</td>
<td>No visible erosion</td>
<td></td>
<td></td>
</tr>
<tr>
<td>10 April test 1</td>
<td>0.8 m / 5.0 s / 3800 s</td>
<td>5600 s (1 h 33 min)</td>
<td>No visible erosion</td>
<td></td>
<td></td>
</tr>
<tr>
<td>11 April test 1</td>
<td>0.9 m / 5.0 s / 2550 s</td>
<td>8150 s (2 h 16 min)</td>
<td>Block erosion</td>
<td>Row H</td>
<td>Block erosion occurs close to the observation window</td>
</tr>
<tr>
<td>16 April test 1</td>
<td>0.5 m / 4.0 s / 4400 s</td>
<td>12550 s (3 h 29 min)</td>
<td>Block erosion</td>
<td>Row J-L</td>
<td>Clay is removed in a joint between two grass sods</td>
</tr>
<tr>
<td>16 April test 2</td>
<td>0.5 m / 4.0 s / 4400 s</td>
<td>16950 s (4 h 43 min)</td>
<td>No visible erosion</td>
<td></td>
<td></td>
</tr>
<tr>
<td>16 April test 3</td>
<td>0.5 m / 4.0 s / 4400 s</td>
<td>21350 s (5 h 56 min)</td>
<td>No visible erosion</td>
<td></td>
<td></td>
</tr>
<tr>
<td>18 April test 1</td>
<td>0.7 m / 5.0 s / 5000 s</td>
<td>26350 s (7 h 19 min)</td>
<td>No visible erosion</td>
<td></td>
<td></td>
</tr>
<tr>
<td>18 April test 2</td>
<td>0.7 m / 5.0 s / 3000 s</td>
<td>31350 s (8 h 43 min)</td>
<td>No visible erosion</td>
<td></td>
<td></td>
</tr>
<tr>
<td>22 April test 1</td>
<td>0.7 m / 5.0 s / 5000 s</td>
<td>36350 s (10 h 6 min)</td>
<td>Block erosion</td>
<td>Row I-L</td>
<td>Several blocks of 10 x 5 cm are removed</td>
</tr>
<tr>
<td>22 April test 2</td>
<td>0.9 m / 5.0 s / 4100 s</td>
<td>40450 s (11 h 14 min)</td>
<td>Block erosion, aggregated erosion</td>
<td>Row M-ML</td>
<td>Small lumps with roots start to erode; visible aggregated erosion</td>
</tr>
<tr>
<td>22 April test 3</td>
<td>0.9 m / 5.0 s / 750 s</td>
<td>41200 s (11 h 27 min)</td>
<td>Block erosion</td>
<td>Row I-L, M-ML</td>
<td>Block erosion next to the joint</td>
</tr>
</tbody>
</table>

According to Table 4.4, no erosion was observed at the first test with mild wave conditions. There could not be seen any erosion holes, however it is expected that minor aggregate erosion occurred. This aggregated erosion caused at this stage of the first test phase only minor and gradual damage of the dike surface in the order of few centimetres.

As mentioned before the first severe damage in the form of block erosion occurred during the test on April 11 in Row H. A large block was eroded next to the observation window presumably due to a combination of reduced wall friction at the glass observation window and damage induced by wave impact pressures in the crack between the window and the grass sod. Also the eroded section was adjacent to a joint and worms were found at the surface of the erosion hole; consequently the grass mat was locally highly permeable.

During test 1 on April 16 clay is removed at the right top side of the left grass mat in Row J. Since the removed clay portion was part of the filling between the joints, it is not representative for the grass cover. All clay that was used to fill the joints between the grass sods...
mats was without root penetration and only small adhesion to the dike surface. Hence, it was easily exposed to erosion by wave impact.

Block erosion continued during the first test on April 22 in Row I, where several clumps with roots were washed out. It is difficult to determine exactly where these eroded blocks came from, but probably from grass mat I-L. Also during the second test several blocks having sizes between 5 x 5 cm and 5 x 15 cm were eroded from the dike surface. The erosion locations could not be determined during the test except from some damage at the bottom left corner of the grass mat M-ML. It was also observed that smaller pieces of roots were washed up during test 2. That indicated the beginning of incipient aggregated erosion during these test.

Aggregated erosion as well as block erosion was also observed during test 3. Especially grass mat I-L was damaged severely as a large part of the grass mat next to the lower joint was removed. The depth of the erosion hole in the grass cover varied between 7 cm and 10 cm. Furthermore, worms were observed at the surface of the erosion hole.

![Overview of rows to identify damage and location of the pressure transducers on the seaward dike slope (Mous, 2010).](image)

Figure 4.16 Overview of rows to identify damage and location of the pressure transducers on the seaward dike slope (Mous, 2010).
5. Test results: Wave overtopping

The objective of the overtopping experiments was to investigate the effect of wave overtopping and run-down flow on the landward grass cover. The installed overtopping container (see section 3.6.4, Figure 114) captured a part of the overtopping water through the inlet. The width of the inlet could be changed between 0.35m and 0.15m. The integrated load cell continuously recorded the changing weight of the container, which was caused by the entering overtopping water and by the decreasing water level due to pumping. Also in phase 2, the grass cover was inspected after each test run.

5.1 Test program

The applied wave spectra was again based on a TMA spectrum, which is a modified JONSWAP spectrum accounting for limited water depth. Table 4.1 gives an overview of the hydraulic parameters of each test run, i.e. peak period $T_p$, the significant wave height $H_s$ and the water depth $d$.

<table>
<thead>
<tr>
<th>Hydraulic Parameter</th>
<th>April 28</th>
<th>April 30 / May 5</th>
<th>May 5 / May 6 / May 7</th>
<th>May 9</th>
</tr>
</thead>
<tbody>
<tr>
<td>$T_p$ [s]</td>
<td>5.0</td>
<td>5.5</td>
<td>6.0</td>
<td>6.5</td>
</tr>
<tr>
<td>$H_s$ [m]</td>
<td>1.0</td>
<td>0.75</td>
<td>0.85</td>
<td>0.9</td>
</tr>
<tr>
<td>$d$ [m]</td>
<td>4.7</td>
<td>5.0</td>
<td>5.0</td>
<td>5.0</td>
</tr>
<tr>
<td>No. of tests</td>
<td>3</td>
<td>2</td>
<td>5</td>
<td>2</td>
</tr>
<tr>
<td>Performed tests</td>
<td>April 28 test 1&lt;br&gt;April 28 test 2&lt;br&gt;April 28 test 3</td>
<td>April 30 test 1&lt;br&gt;April 30 test 2&lt;br&gt;May 5 test 1</td>
<td>May 5 test 2&lt;br&gt;May 5 test 3&lt;br&gt;May 6 test 1&lt;br&gt;May 6 test 2&lt;br&gt;May 7 test 1</td>
<td>May 9 test 1&lt;br&gt;May 9 test 2</td>
</tr>
</tbody>
</table>

5.2 Analysis of overtopping records

The installed overtopping container was used to collect a certain part of the overtopping water. The load cell of the overtopping container recorded continuously the changing weight of the container due to the inflow of overtopping water through the inlet as well as due to the lowering of the water level in the container by pumping out the water. Before the tests on May 9, the opening of the inlet was reduced from 20 to 15 cm as the inflow volume was larger than the remaining time between to overtopping events where water had to be pumped out of the container.
The overtopping discharge was continuously measured over the entire test duration of test phase 2. Both the individual and average overtopping discharge and their influence on the grass sods were analysed.

![Figure 5.1 View from the dike crest.](image1)

![Figure 5.2 View from the area behind the dike model.](image2)

![Figure 5.3 Record of the changing water volume in the overtopping container (Test 28040802).](image3)

Different distinctive points can be seen in Figure 5.4. In Point ‘a’ water flows into the container and its weight increases. In point ‘b’ a constant water level in the overtopping container can be noticed. When the maximum possible water level was reached in the container, the water was pumped out and the pressure decreased. This action can be seen by the vertical line in point ‘c’. At the end of pumping out the water, the pressure increased again immediately (point ‘d’). This effect was caused by water that was flowing back from the hose into the container after the pumps were switched off.

Besides recording the load of the container, the start time and end time of pumping water out of the overtopping container, was written down. The start and end time of pumping...
actions according to the record in Figure 5.5, are listed in Table 5.2. In the case that water had run-over the container walls, a remark was made in the table.

**Table 5.2 Start and end of pumping action (overtopping test 280408).**

<table>
<thead>
<tr>
<th></th>
<th>Start</th>
<th>End</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>12:23:07</td>
<td>12:24:04</td>
<td></td>
</tr>
<tr>
<td>2.</td>
<td>12:24:48</td>
<td>12:25:52</td>
<td></td>
</tr>
<tr>
<td>3.</td>
<td>12:30:17</td>
<td>12:30:27</td>
<td></td>
</tr>
<tr>
<td>4.</td>
<td>12:30:42</td>
<td>12:31:15</td>
<td></td>
</tr>
<tr>
<td>5.</td>
<td>12:35:32</td>
<td>12:36:02</td>
<td></td>
</tr>
<tr>
<td>6.</td>
<td>12:41:27</td>
<td>12:42:00</td>
<td></td>
</tr>
<tr>
<td>7.</td>
<td>12:45:40</td>
<td>12:46:07</td>
<td></td>
</tr>
<tr>
<td>9.</td>
<td>12:54:05</td>
<td>12:54:12</td>
<td></td>
</tr>
<tr>
<td>10.</td>
<td>12:55:00</td>
<td>12:55:58</td>
<td></td>
</tr>
<tr>
<td>11.</td>
<td>13:06:32</td>
<td>13:07:10</td>
<td></td>
</tr>
</tbody>
</table>

**5.3 Damage observations**

During the wave overtopping tests, no severe damage of the landward grass cover due to wave overtopping was observed. It was, however, observed that larger aggregates were washed over the dike crest. These aggregates originated from the outer slope and showed that the outer slope was damaged continuously. Even during the all tests on May 5, 6, 7 and 9 no damage on the inner dike slope was observed in spite of overtopping volumes larger than 30 l/sm. Even at the inner dike foot, where the run down direction of the overtopping volume changes into a horizontal direction and the largest run-down velocities appear, no damage of the grass cover was observed.
6. Colour range analysis considering video recordings

The initiation and progression of erosion on both dike slopes were registered by video recordings. All tests were recorded by two digital video cameras. The two digital JVC cameras, including a hard disk of 60GB (GZ-HD3E), produced videos with a resolution of 1440x1080. The locations of the video cameras were changed depending on the test phase. During wave impact tests (phase 1) the digital cameras were installed at the southern gangway of the flume (Figure 6.1), one camera pointing towards the seaward slope (Figure 6.2) and the other camera pointing in opposite direction (Figure 6.3).

![Figure 6.1 Camera locations during wave impact tests (phase 1).](image1)

![Figure 6.2 View from camera 1.](image2)

![Figure 6.3 View from camera 2.](image3)

During wave overtopping tests (phases 2) the digital video cameras were also installed at the southern gangway of the flume (Figure 6.4). One video camera was installed above the seaward slope pointing towards the dike crest (Figure 6.5). The second camera was installed at the landward side of the dike model pointing towards the landward slope (Figure 6.6).

![Figure 6.4](image4)

![Figure 6.5](image5)

![Figure 6.6](image6)
In the process of analysing all test data and observations, considerations were made to include the video recordings in the analysis of the experiments. As the green colour of the grass cover changes to a less green colour with continuous wave impact, the idea was to use this change in green colour in order to make conclusions about the quality and strength of the grass cover on the outer dike slope. A method was therefore derived to determine the grass cover strength from video recordings. The method considers the pixel values of pictures taken from the video recordings. The method was developed within a research project by Christensen (2011) and is called the *green-value method*. In the following, the work by Christensen is described.
6.1 The green-value method

Colour images can appear in various formats such as RGB (Red-Green-Blue), which is one of the most common digital formats (Christensen, 2011). In the RGB-format a pixel consists of three different values: one for each three basic colours red, green and blue. In the case, a pixel displays a green colour (cp. Figure 6.7) the green value will be high while the other values are close to 0. A given colour is therefore calculated as the ratio of the three values, while the sum of the values indicates the shade of the colour (the higher the value, the lighter shade).

The green-value method considers an average pixel value in specific areas of an image series. The development of this average value can be compared over time or wave load, as shown in Figure 6.8.

The main objective of the work by Christensen (2011) was to identify indicators for assessing the properties and condition of a dike using images from the video recordings. The method therefore had to be based on the values of the different pixels of the image.

The primary indicator was the green value of a relevant area on the dike slope in a RGB image. The green value is of particular interest because an intact turf naturally will be green. During surge load the dike grass cover can gradually erode and a change in the green colour can be observed when the leaves on the grass are eroded away. Ultimately, the complete erosion of grass cover will produce the colour of the underlying clay layer. The green value in an RGB image will then be able to indicate whether the grass cover is intact or not. Additionally, Christensen intended to develop the green-value method to be able to indicate about the development of weak spots and incipient erosion of the grass cover.

The green-value method considers an average pixel value in specific areas of an image series. The development of this average value can be compared over time or wave load, as shown in Figure 6.8.

![Figure 6.7 Examples of several shades of the same colour in the RGB-format.](image)

![Figure 6.8 Green-value development over time (Christensen, 2011).](image)
Referring to aggregate erosion and block erosion, Christensen (2011) argued that there will only be erosion of the upper loose material at first. When aggregate erosion reaches the top of the root system, the grass cover achieves its greatest strength. It is therefore expected that the green value declines slowly at this stage. When erosion, however, progressed and the root system of the grass cover is damaged, he expected a rapid decrease in the green value until it eventually flattens out and changes to the colour value of the underlying clay. At block erosion he expected a sudden drop of the green value to a colour value of the underlying clay, since the entire grass cover is locally removed.

At the same time the following assumptions have to be made with the green-value method:

The specific elements (e.g. grass leaf) do not change colour. It is expected that the grass leaves retain their colour, and do not become discoloured due to contamination from e.g. clay particles. Likewise, it is expected that the clay particles do not change colour.

The grass cover has during all stages of erosion a different colour than the clay. A problem arises, therefore, if all leaves eroded away and only the root system remains, since the root system does not have the same green colour as the leaves. It is, however, expected that there will always be a certain amount of leaves left on the grass cover and, hence, the concentration of leaves and the related green-value indicate the stage of erosion. The exact correlation between the erosion of the leaves and roots due the aggregate erosion, and thus the loss of strength, must still be verified.

Besides these assumptions, the lighting conditions had to be known throughout all experiments because varying lighting conditions will be reflected in the colour values on the dike. Therefore, the green-value method had to consider an ongoing assessment of the lighting conditions, which was used to correct the green values.

As mentioned above, the sum of the RGB-values indicate the hue. Large values will produce a light shade and small values a dark shade. Therefore, a stronger illuminated dike leads to
higher green values. It was therefore necessary to measure the brightness at a neutral location on the images for correction. It could be in an undisturbed part of the dike or on the wall of the flume. At irregular illumination the neutral location had to be selected close to the image region of interest and on a surface with roughly the same orientation as the dike, since the reflections from this irregular illumination will be more or less identical and make the correction more accurate. These neutral locations and the measured colour values are referred as control fields and control values.

6.2 Control fields and green-value correction
The experiments in the Large Wave Flume were not designed for colour range analyses considering video recordings as the primary purpose. The locations of the cameras were generally not optimal and changed slightly every day, as the cameras were packed every evening to avoid burglary.

The cameras are positioned on top of the balustrade of the flume wall giving the images a skewed perspective to the dike slope. Besides that, the changing light conditions made image processing difficult. The lighting conditions consisted of both natural light through windows in the flume hall and artificial light from projectors. The projectors gave a constant contribution to light, but the natural lighting through the hall windows varied throughout the day and during each test.

Since direct daylight through a window influences very local areas of the image, several control fields were necessary, so that local light variations at one control field do not result exclusively in correction of the green-value data. Optimally, the control field should be located close to the study area with roughly the same orientation to give identical conditions. It was therefore important to determine the influence of the natural light fluctuations on the study area on the dike slope. Furthermore, it was important to investigate if the study area was primarily illuminated by artificial or natural lighting. Large fluctuation of the natural light in a control field resulted in large correction of the green-value data of the study area. If the study area was primarily lit by spotlights, the observed fluctuation in the control fields were small and a correction by a control field with natural light incidence might have been wrong. The corrections of the green-value data had therefore not only to be equal from the control field to the study area, but had to be adapted to the particular condition from the control field to the study area.

To illustrate this argument, two control fields, field 1 and 2, are defined where field 1 is located at a hall window with natural light incidence. Field 2 is located down in the wave flume and, hence, in the shadow of the hall windows (see Figure 6.10). In this way, field 2 is less influenced by natural light incidence than field 1. In return, field 2 is more exposed to constant artificial lightning than field 1.
The lightning condition shown in Figure 6.10 can be written as follows:

\[ Y_1 = aX \]
\[ Y_2 = bX + k \]

where \( Y \) denotes the overall lighting in a given field, \( X \) indicates the intensity of light and \( k \) describes the permanent artificial lighting that the control field receives. The parameter \( k \) might be equal to 1 at all times, \( a = 1 \), \( b = \frac{1}{2} \), and let \( X \) be set to 4 the first day, followed by \( X \) being 6 the next day, the obtained illumination of both fields is shown in Table 6.1.

**Table 6.1  Example of different development of the control fields.**

<table>
<thead>
<tr>
<th>( X )</th>
<th>( Y_1 )</th>
<th>( Y_2 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>4</td>
<td>4</td>
<td>3</td>
</tr>
<tr>
<td>6</td>
<td>6</td>
<td>4</td>
</tr>
</tbody>
</table>

Instead of the control field 1 being 33\% stronger than the illuminated control field 2, the lighting is now 50\% stronger. So it can be seen that the location of the control fields in relation to the lighting makes a difference, not only in the total amount of light on the spot, but also in the size of the fluctuations due to changing lighting conditions.

The measured green values of the study area have to be corrected by the control values in order to considered variations in the light conditions. If the control field is as sensitive to changes in the daylight conditions as the study area, the green values of the study area are corrected as follows:

\[ g^* = \frac{g}{g_0} \frac{k}{k_0} \]

where \( g^* \) is the dimensionless adjusted green value, \( g \) is the measured green value and \( k \) is the measured control value. Moreover, \( k_0 \) and \( g_0 \) are constant values that are defined by
selecting a total lighting, which is assessed as normal. The purpose of these constant values is to make the control value and the measured green value of the same magnitude as changes in the values due to changing light conditions can be compared, regardless of the colour of the fields.

However, if different dependencies of the natural lighting have to be considered, so that fluctuations in the natural lighting give different relative changes in the green value, an additional corrective factor must be introduce that takes into account how much of the natural light influences the light exposure of the study area:

\[ g^* = \left( a \cdot \frac{g}{g_0} \right) / \left( b \cdot \frac{k}{k_0} \right) \]

where \( a \) is the relationship between the current lighting on the study area and the total light incidence in the hall. Correspondingly, \( b \) is the relationship between current lighting on the control field and the total light incidence. It is, however, required that these lightning conditions are measured during the experiments, but this has not been done during the EroGRASS project. The following analysis of the development of the green values considers therefore only the correction according to the first form.

### 6.3 The development of the green-value

In order to optimise the analysis of green-values, software was developed to measure and analyse the green values and control values as well as to handle the image frames from the video recordings. The program is written in LabView and NI Vision Development Enlargement.

The user of the program can select a range on the dike slope and a control area, as seen in Figure 6.10. The program then divides the range into a rectangular net of any size. In each field, the program finds the average green value of all pixels in the field and stores these average values in a spreadsheet as a 2D array. The values from one study area and multiple images at different times show the development of the green value, as outlined back in Figure 6.11.

![Selection of a range on the dike slope.](image)
For the selection of the image frames, it was important to select frames where the study area was free of water. Water coverage of the study area changes the colour dramatically, and the green-value data will be useless. It was also paid attention to avoid image frames with extreme lighting conditions or images with strong reflections or shadows.

The measured green values are shown in Figure 6.12. The uncorrected green values can be read together with several suggestions of corrections of the green-value development, as each control field is added by a graph. In addition, the green-value developments are corrected by an average of the control values.

![Figure 6.12 Green-value development over number of waves.](image)

The red curve in Figure 6.12 shows the uncorrected green values, while the orange curve (circular markers) indicates the green values corrected by an average of the control values. It is observed that during test phase 1 (wave impact) the green values for the study area just above the breaking zone fairly steady decline. However, large differences between the developments in the control fields can be seen being a clear sign of changing light conditions. With respect to the other study areas, the large variations in the green-value developments did not make a clear interpretation of these data possible.

The introduction of control fields implicated several other problems of using the video recordings from EroGRASS experiments. The overriding problem was the light conditions in the flume, not only on different days but also during each experiment. An example is shown in Figure 6.13.

Control fields 1 and 2 are located on the flume wall as far down as possible without being covered by water. Thus, they were located roughly at the same level as the study area. Control fields 3 and 4 were located on the dike above the study area in order to avoid any wave load during testing. Control field 5 is the only field located outside the flume, and is selected as the surface on which the control line is located.
As it can be seen in Figure 6.13, the study area and the two control fields on the dike slope follow a fairly similar green-value curve. Green-value curve of the study area is, though, observed to start higher, but finishes equal to the two control field curves.

The values of the other three control fields are increasing during the experiments, indicating an increase in lighting during the day. This makes also sense as most experiments were performed before noon (13 o’clock DST) when the sun was strongest. The variations of the green-value curves of the three control fields are matching, except of the large fluctuation just prior to the wave number reaches 4000. Control field 1 and 2 increase shortly, while control field 5 drops. The reason for this could be a sudden change in the incidence of light from the sun, meaning that the camera shut down some of the extra light. In this way, areas that may not be directly illuminated by extra light will instead appear darker than before and thereby cause a drop of the green value. In this case, it is even more essential that the control field is located nearby with the same orientation as the dike slope.

For the study area and the control fields 3 and 4, the green-value curves seem to decrease slightly and only very small fluctuations in the green-value curves are observed. In addition, the three curves follow each other well with almost the same green values. Something seems however wrong as the curves of the study area and the two control fields on the dike decrease, whereas the curves of the other control fields are increasing sharply. Whether
there are other noise sources that cause this ambiguity, are not to answer before taken into account the already discussed problems and have to be investigated in further research work.

During the derivation of the green-value method other visual indicators of the dike were also investigated. Among them, it was desirable to automatically identify and separate other elements of the flume, such as grass, foam, flowing water and standing water. A second software application was developed in another research project at the Institute of Mathematical Modelling (IMM) at the Technical University of Denmark by Sørensen (2011). Sørensen (2011) developed a program that precisely identifies different elements of an image. For calibration and testing of the program he used 100 images from one of the EroGRASS experiments. Based on these 100 pictures, where one picture was taken per second, we managed to identify all areas of the images with 85% accuracy. Taking lighting and camera angle into consideration, it was concluded to be a very good result. For further information about the program, the reader is referred to Sørensen (2011).

6.4 The correlation between the green-value method and grass erosion

The green-value method is based on the assumption that a decrease in the green value indicates erosion of the grass cover. It is substantiated on logical arguments in this chapter, but exact relationship is not known yet. It is therefore important to investigate this relationship in order to convert a decrease of the green value into an erosion depth, or with other tangible parameters for grass erosion.

In this respect, the simultaneous investigation of the secession of aggregates and the measuring of green values is important. This is considered important as the green leaves are the visible surface of the dike, while the strength of the grass cover comes from the root system. It is therefore necessary to study whether erosion of leaves and erosion of the root system are coherent, and whether this occurs e.g. in serial order, so the roots only are eroded when the leaves are removed, or if the erosion of leaves and roots occur at the same time. In this case, a decrease in the green-value could be directly transferred to the erosion of the root system, and thereby to a decrease of the grass cover strength.

The experiment to be carried out, should measure the green value and the erosion depth between a certain numbers of waves. Thus, it would be possible to investigate how much the green value has fallen before aggregate erosion can actually be measured. Furthermore, it can be investigated whether there is a continuous relationship between a decreasing green-value and the erosion depth or other grass erosion parameters.

Alternatively, a larger number of grass sods could be exposed to varied wave load durations while green values are measured, followed by a destructive analysis to assess the tensile strength of the grass sods. In this way, the grass sod strength could be compared with the measured green values in order to clarify whether there is a direct correlation between the green values and the actual strength of the grass cover.

These experiments can be performed in smaller experimental setups than the EroGRASS experiments since the grass sods remain in full scale although the experimental setup would be smaller.
7. Conclusions and recommendations

The main objectives of the EroGRASS project was to perform large scale model tests in order to investigate the erosion of the highly erosion resistant layer of the turf and the lifting of the turf near the subsoil. The most important conclusions of both test phases and the respective observations made during the tests are presented in Section 7.1 together with the conclusions of the developed green-value method. Section 7.2 contains recommendations for further research in relation to the large scale model tests and the green-value method.

7.1 Conclusions

Predicting the erosion of particularly this highly erosion resistant zone is very important as it is the toughest part of the grass cover. When this tough layer has been eroded away the erosion rate will dramatically increase and the damage will be ongoing. Erosion of the highly erosion resistant zone can therefore be considered as the point of no return and has be defined as a critical erosion depth, which in general corresponds with the underside of the highly erosion resistant layer which is estimated to be at a depth of 5-7 cm. The critical erosion depth can be related to the critical root density.

Considering the wave impact tests (phase 1), wave induced erosion of the grass cover layer can occur due two independent failure mechanisms:

- Aggregate erosion, initiated due to the crack of the soil by uplift pressures, which are caused underneath the aggregates shortly after wave impact. At the dike surface small aggregates are then lifted and washed away, which eventually results in an erosion hole.
- Block erosion, initiated by impact pressures that penetrate into the soil via large cracks. A horizontal crack is formed at the location of minimum fracture strength. This crack gradually extends until it reaches a critical size and a large block can instantly erosion leaving a large hole in the grass cover.

The tests at the outer dike slope showed that erosion develops sooner at weak locations such as dead plants or bare spots than at locations where the sod is densely rooted. At well rooted locations erosion will mostly not occur, however they can be affected by a weak spot in their vicinity. Weaker spots are therefore more vulnerable to different types of loading and will erode faster.

All large erosion holes were located adjacent to joints of the grass sods, which makes also the assumption that erosion is initiated at weaker locations highly plausible. Inevitably the joints between the grass cover sections had cracks, which remained after installation of the grass sods. And even if no cracks were present initially at the joints, it is supposed that these were generated at a later stage when the clay in the joints was washed out due to wave loads and the fact, that the clay is not rooted.

It is further assumed that another factor could have played a part in the erosion processes during the wave impact tests; worms were found in the erosion holes in grass mat I-L and H-R, which probably weakened the turf as well. Block erosion occurred in the form of clumps with a width varying between 5 and 70 cm. The diameter of eroded blocks varied generally between 5 cm and 15 cm, which were ripped from the subsoil at a depth of the 7 cm to 10 cm.

With respect to aggregate erosion, it can be concluded that the tests with a significant wave height of 0.5 m generally posed no problem for the grass cover. Erosion rates were
accelerated during tests with a significant wave height of 0.7 m but only minor damage was caused. Only during the tests with a significant wave height of 0.9 m significant damage was inflicted. As the tests with significant wave heights of 0.9 m were performed at the end of phase 1, the increase of aggregate erosion and significant damage on the outer slope must also be seen in the light of a cumulative degradation of the turf layer from test to test. As the wave impact tests were performed one after another with a few days of interruption, the grass cover had not enough time to recover after each test event. This circumstance represents in reality a chain of storm surges at frequent intervals (few days).

Two successive storm surges with a few days in between have been observed in periods, however, 5-6 successive storm surges at intervals of 2-3 days, such as performed in phase 1, have not been registered yet. The frequent wave impact intervals during phase 1 must therefore be considered as an enhanced loading of the grass cover layer on the outer slope that is normally not naturally occurring.

The wave overtopping tests at the inner dike slope showed no damage at the grass cover at all. Even during tests with overtopping volumes between 25 l/sm and 30 l/sm no damage at the inner slope was found. Also at the inner dike foot, where the run down direction of the overtopping volume changes into a horizontal direction and the largest run-down velocity appear, the grass cover stayed undamaged. However, large aggregates were washed over the dike crest. These aggregates originated from the outer slope and indicated that block erosion on the outer slope continued to an increasing degree during phase 2. This underlines the increased degradation and destruction of the grass layer on the outer slope with cumulative wave impact.

The green-value method was developed based on video recordings to detect damages in the grass cover. For this purpose, the green value is measured in pre-defined study areas on RGB-images. The green value is defined as an indicator of grass cover condition. It is expected that leaves of the grass are removed due to erosion, implicating a decrease of the green value of a certain area on the dike slope. It is expected that the erosion rate of the grass cover will vary due to the strength of the different layers of grass cover. The slope of a green-value curve will therefore vary.

The EroGRASS experiments were used to verify the application of the green-value method. The quality of the video recordings was however too poorly due to highly variable lighting conditions, changing camera settings and suboptimal camera locations. Therefore, the method could not be demonstrated and verified. However, recommendations for future studies were made and potential weaknesses of the method were detected.

The two main recommendations are that the exact relationship between the erosion of the grass cover and the decrease in the green value have to be investigated, as well as future experiments and of video recordings have to be performed at controlled artificial lighting, as most sources of noise came from the naturally varying illumination from the windows of the hall. Under such controlled conditions the green-value method is assumed to be useful with good application potential.

On the whole, the tests performed in the EroGRASS project show a high erosion resistance of well-maintained grass cover layers, i.e. the performance of a grass cover layer depends primarily on its management. High erosion resistance is achieved through a close turf with fine and coarse roots. The tests at the outer slope also showed that this high erosion resistance decreases at locations where the grass cover is less maintained and the sod is
densely rooted. Weaker spots are therefore more vulnerable to wave loading and erosion. Maintenance of the turf layer is therefore essential for the grass cover strength. The tests showed further, that aggregate erosion and block erosion is dependent on the frequency of loading events. A large number of wave loading events at frequent intervals with few days in between will not give the grass cover enough time to recover after each event. A chain of frequent loading events will therefore provoke degradation of the grass cover layer on dike slopes and, from a certain point of time, increase destruction of the grass cover layer dramatically.

7.2 Recommendations

Due to constructional reasons the grass cover of the EroGRASS experiments consisted of several grass sods which were assembled on both dike slopes. Inevitably this led to irregularities at the surface and joints between the sods. Although these joints were filled up and repaired when damaged, these irregularities had a significant influence on the erosion process. The installation method as well as the method to excavate the grass sods should therefore be improved. A potential improvement of the installation could be to close off part of the flume and to assign this space to a dike model with a grass cover, in such a way that the grass cover is given sufficient time to recover from the installation. Furthermore the erosion of the grass has to be monitored in more detail. The surface erosion depths could be measured with plaster casts or lasers. In addition more pressure transducers could be installed to investigate the pressure variation with respect to depth.

With respect to the green-value method and the imaging, the experimental setup during the EroGRASS project was not optimal. Variations in lighting and impractical camera setup made the image processing uncertain. As the green-value method is very sensitive to the mixed lighting and camera placement, it is recommended that any new experiment has to be carried out under a more controlled environment.

Optimally, the experiments should only be performed with constant artificial lighting, since the natural lighting allows variations in illumination. Before the beginning of the experiment, the light conditions on all parts of the dike have to be measured, for example by using a simple light meter. In this way a map of lighting throughout the dike can be produced and used for correction of the green values. Moreover, it must be ensure that there are no strong reflections or shadows on the dike when using artificial lighting, as these can complicate image processing.

Another recommended change in the experimental setup is the placement of cameras. It is recommended that a camera is placed above the centre of the dike at greater angle than in the EroGRASS project. In this case the outer dike slope will disperse perpendicular to the vision field of the camera. A more direct perspective will visualise the entire outer slope of the dike, making the determination of lengths and areas much easier, and may eventually open the possibility that video recordings can be used for a digital model of the dike and wave impact. Alternatively, two cameras can be set up stereo, on both sides of the flume. This will allow for the preparation of 3D-information of the dike, which can be stored digitally for further modelling. Here, it is essential that both cameras are synchronized with respect to time.

Furthermore, video recordings of the dike should also be made when the flume is emptied to record the grass cover in the breaker zone just below the mean water level. Otherwise, the breaker zone is covered by water more or less constant during the tests.
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