TAW Technische Adviescommissie voor de Waterkeringen

Technical Advisory Committee for Flood Defence in The Netherlands

TECHNICAL REPORT

EROSION RESISTANCE OF GRASSLAND AS DIKE COVERING

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Contents

APPENDICES

1. Introduction

Almost all river dikes and most of the sea dikes in the Netherlands are covered with grassland, and the erosion resistance of these dikes is determined by the strength of that covering. This strength is strongly dependent on the way in which the grass is managed and the properties of the soil. The requirements for erosion resistance depend on the hydraulic load. This report concerns the stability of grass coverings against the erosion caused by the loading put on them by waves. Until 1990, there was almost nothing known about this subject. Six years later, there is more to say about design, maintenance and testing of grass mats and the first attempt at a model has been made.

Reason for this study

Old dikes are usually still constructed entirely from clay and since 1953 many much heavier dikes have been made from a core of sand with a covering. This construction puts heavier requirements on the covering, as it also does for grassland on a clay layer. These and other developments have led to the need for more insight into the strength of grassland as a dike covering and into the possibilities of managing it better. Regular maintenance is essential for grass coverings and furthermore they are relatively sensitive in their early years to damage; even somewhat older grass coverings sometimes show signs of unexpected damage. They require expenditure to put right and cause doubts about their strength under extreme circumstances.
In addition, the Flood Defences Act requires an evaluation every five years of the existing primary flood water defences, of which the dike coverings form an important part.
Dike managers have an inclination to put a hard covering on a dike because there is so little insight into the strength of grass coverings, thereby contributing to the reduction of herbage-rich grasslands. As a result, the other functions of dikes, such as the preservation of environment, landscape and culture-history values (abbreviated in Dutch as LNC-values), recreation and agriculture get less attention. Because dikes play a water defensive role before everything, other functions can only be considered if the required erosion resistance of the covering is sufficiently durable. Safety against water is the primary goal, for river, sea and lake dikes. This study has also been aimed at increasing insight into the strength of grassland as a dike covering and on measures that can increase the desired strength.

Objectives of this report

The Technical Advisory Committee for Flood Defence (TAW) has published the occasional brochure and manual since the early 1980s about construction, management and maintenance of grass, as a service to dike managers [TAW, 1981]. Since 1990, research into grassland has been approached structurally in the so-called Grass Plan. This study is intended to answer questions from practical experience of construction and maintenance of dikes. In recent years, some studies have been completed under the auspices of TAW and sponsored by the Road and Hydraulic Engineering Institute of the Directorate General for Public Works and Road Engineering. However, the research reports are only accessible for a very small target group. For this reason, and partly also in relation to recent experiences with high water levels in the Large Rivers in the Netherlands, the results are being summarised and distributed more widely. Therefore, the objective of this report is as follows:

> *To provide clarity about the erosion resistance of grassland as a dike covering under hydraulic loading from waves and to make recommendations regarding the balance between grassland and a hard dike covering, the efficient management of a grass covering, the evaluation of an existing grass covering during safety monitoring, and the possibilities for improvement of the composition and strength after a satisfactory evaluation result.*

The accent in this report lies on the erosion resistance of grassland as a dike covering, i.e., on the question of whether it is strong enough at normal and extreme loads. Damage (or behaviour) models are used for making an appropriate evaluation of the grass mat as an independent element. In this model, the relationships between soil type, bank slope, vegetation, management, rooting behaviour and strength are the main features. Damage models for run-off from steep (inner) banks by shallow run-off of over-topping water and for the grass mat as part of the flood water defences for an inundation-risk approach, in which the remaining strength of the clay under the sod plays a role, fall outside the scope of this report.

The conclusions and recommendations of this report are intended for inclusion into TAW guidelines, brochures and in the earlier-mentioned manual for the management of green dike coverings. They can be directly applied in the management, maintenance and construction of dikes. Alongside this, the insights described here serve as a basis for adjusting the evaluation rules in the Monitoring Safety Guide.

2. Conclusions and recommendations

A number of general conclusions can be drawn about grassland on river, sea and lake dikes, on the basis of the studies that form the foundation of this report:

Grass is capable of withstanding considerable wave loads when used as a dike covering. Waves that occur in the Large Rivers area are no problem for a good erosion-resistant grass mat. Sea and lake dikes show no damage after waves of 0.75 m (and possibly higher) on a similar closed grass mat with a high root density. Management is the governing factor here: unfertilised hay-making and lightly fertilised grazing leads to a strong sod. After sowing on bare ground, the grass mat is at good strength after three to five years.

Unfertilised hay-making leads to the highest erosion resistance and is simple to organise. Lightly fertilised grazing leads to good erosion resistance, but is more complicated to organise, because it must take place in short periods with a biomass production that is accurately matched to the number of cattle. In addition, extra maintenance is necessary for the grass mat and the cattle grids.

For dikes in the Large Rivers area, sufficient is known to allow formulation of requirements for a grass mat that is strong enough to resist the common hydraulic loads. This is also true for grass coverings of sea and lake dikes, as long as the waves are no higher than 0.75 m. There is no grassland management method yet formulated that will cope with wave heights greater than 0.75m without the waves causing some damage. There is also no appropriate method for establishing the presence of the required strength.

2.1. General conclusions and recommendations

- A grass mat with a high erosion resistance consists of a closed growth and a high root density in the 0 - 0.15m layer. For hay meadows, a coverage of > 70% is required with an even distribution of shoots; for grazing pasture, a coverage of >85% is recommended.

The strength is mainly in the non-visible part: the root layer. The achievement of a close grass mat and thick sod penetration depends on the type of management used and, less importantly, on the properties of the soil. With correct management, the erosion resistance of sod is better than that of good erosion-resistant clay.

- The removal of produced crop by hay-making or grazing is essential for sod formation. Furthermore, it also depends on the amount of fertilisation: unfertilised hay-making and lightly fertilised grazing (to a maximum of 75 kg N per hectare per year) leads to a strong sod. The management methods that are appropriate here fit in with the various categories of management for river dikes: hydraulic, adapted farming and natural technique [Fliervoet, 1992]. If the grazing areas remain without grass, they must still be mown, after which the cuttings must be removed. The best method for grazing is to allow many sheep to graze an area for short periods at a time, then allow a number of weeks rest.

- The grass covering of the dike when managed using the unfertilised hay-making technique develops not only the desired strength but it also gains a higher value with respect to its nature content, containing a great variety of species with a relatively large number of remaining herbage that is characteristic for the Large Rivers area and are seldom found elsewhere.

- Sod with a low root density has poor resistance to erosion. This low root density occurs in grass mats with many open areas and high-growing plants (including Cow parsnip, Greater stinging nettle, and Cow parsley/Wild chervil). This type of sod occurs when grassland is managed by mowing without removal of cuttings, so-called 'rough mowing'. Intensive fertilisation with grazing or hay-making also leads to a limited amount of sod penetration. This sort of grass mat can appear, incorrectly, to be closed, and will include growth of Shepherd's purse, Bitter dock, Creeping Thistle, Annual Meadow-grass, because the annual types die off in the winter and there is mainly superficial sod penetration with little variation in root type.

- Expansion of management, i.e., stopping or reducing fertilisation, leads to an improvement in erosion resistance. A favourable effect of increased sod penetration occurs within a few years after a changeover from intensive grazing to unfertilised hay-making.

- The type of soil also governs the formation of the sod. From experience with existing grass mats with good erosion resistance, it appears that (moderately) erosion-resistant clay (categories 1 or 2 according the the Technical Report 'Clay for dikes' [TAW, 1996]) is sufficient. A thick network of roots does not develop any faster or better in a more sandy clay, such as that classified as category 3. The erosion resistance of the sod is better, with good management, than that of good erosion-resistant clay.
  When a covering of erosion-resistant clay is going to be applied, a top layer of sandy clay is recommended, with a thickness of 0.25 m (minimum 0.15 m, maximum 0.35 m), with a sand content of maximum 50 % and with some cohesion. Almost all the clay types in the Netherlands conform to these requirements.

- On more sandy clay types, a more richly varied plant community can develop, with characteristic and rare species found along rivers. This natural improvement is another possible reason for using a top layer of sandy clay.

- The loading on the dike bank as a consequence of water flow is less than that from waves a few decimetres high. This loading is never taken as representative if there is also some wave loading.

- Inner banks are loaded by water run-off after wave over-topping. A moderate to good closed grass mat will not show any erosion damage up to an average over-topping volume of 10 l/s per metre.

2.2. Conclusions and recommendations for river dikes

- Waves in the Large Rivers area will be only a few decimetres high during high water. A grass mat with closed growth covering and a high root density is then always sufficient. Small amounts of damage to the grass mat caused, for example, by floating driftwood that is not immediately removed, are not a problem for such a mat. Even if there are holes present, such as mole tunnels, these will not lead to damage, as long as these holes are not larger than about 900 cm^2 and not deeper than 0.10 m. Floating debris should be removed as soon as possible to prevent greater damage occurring to the grass mat.

- If there are doubts about the possibility of maintaining the appropriate type of grassland management, which might lead to wave loading increasing the risks of damage during high water, the underlayer must consist of at least moderately erosion-resistant clay. According to the Guidelines for the Design of River Dikes, the total thickness of the covering layer of clay must be at least 1 m.

- A bank steeper than 1:3 is not a hindrance to allowing grass to grow and therefore the application of a grassland covering. However, maintenance can be more difficult to realise in practice, for example because longer mower arms are needed. The loading from the waves will increase with the steepness of the bank, but this is small compared to the margins in the strength factor.

- Account must be taken of the wave-dampening influence of gradients, in the rate of flow of the river and the water meadows, and in the direction of generation of waves, when determining the wave loading on dikes.

2.3. Conclusions and recommendations for sea and lake dikes

- Waves against the outer banks of sea and lake dikes can reach heights of more than 1.5m. On the basis of known information, it should not be expected that a good grass mat (on a bank of slope 1:3 to 1:4) can resist breaking waves of this height for a sufficiently long time (i.e., for the duration of a heavy storm flood).

- Up till now, criteria have not been available for evaluation of any grass mat for the required quality. However, it has been shown that very good grass mats, on a bank of slope 1:3 to 1:4 and on erosion-resistant undersoil, can stand up to waves of 1.0 m, with no serious damage after more than one day. The damage-free period for waves of slightly more than 1.0 m was shorter, but still long enough to cope with a high water storm flood.

- Good grass mats will not suffer any damage from waves up to 0.75 m during a storm flood. If the slope is even flatter (1:6 and flatter), this is valid also in proportion for higher wave loading.

- The risk of small damage from larger wave heights becoming more serious is much greater for sea and lake dikes than for river dikes. Therefore, the underlayer must always consist of adequate erosion-resistant clay, which must be at least 1 - 1.5m thick, depending on the loading and further construction of the dike.

- The loading from wave run-up for grass mats just above the calm water line (i.e., above the design level during a typical storm flood) is much less than in the wave breaking zone, meaning that the speed of erosion is 4 times slower. The grass mat above the calm water line can resist waves twice as high as grass mats in the wave breaking zone. This is valid for a flat bank with a hard covering that is not too smooth (e.g., Haringman blocks, or basalt), with the transtition to grass covering without upright ridges or cracks.

3. Description of study results

3.1. Civil engineering and botanical study

The study into the erosion resistance of grassland coverings was started initially along two separate and independent lines:

1. From the *civil engineering* viewpoint, by modelling the relationship load - strength - damage;
2. From the *botanical* viewpoint, aimed at answering the question of how to maintain a grass mat so that the vegetation will harbour characteristic and rare species.

It was soon realised that these two lines of investigation should be integrated, to allow two approaches to be followed, one being very time-consuming and offering basic insights, being a more theoretical approach based on analysis of erosion tests. The other approach is a type of '*black box*', that can quickly lead to a useable and simple model of erosion. This does not give insight into the underlying mechanism, which means that the application is limited to an empirically studied situation.
Considering that both approaches are aimed at achieving a model for behaviour or, as the case may be, for damage of grass as an independent element, the methods have become more tuned to each other over the years. One line has been studying the strength of the grassland, the related and relevant erosion mechanism and the causes of erosion resistance. The other line has studied the hydraulic loads of wave attack (water flow rate, wave run-up, wave impact, etc.). In the following paragraphs we briefly summarise the research results from both types of study.

3.2. Composition and strength of grass sod.

3.2.1. Cohesion in the sod

From the first run-off tests on the Knardijk from 1970, resulting in among others a large-scale laboratory study [Burger, 1984], it seemed that a grass mat can show high erosion resistance. This characteristic is found mainly in the structure of the root layer and not, as often thought, in the thickness of the layer of grass leaves and stems above the ground (Figure 3.1).

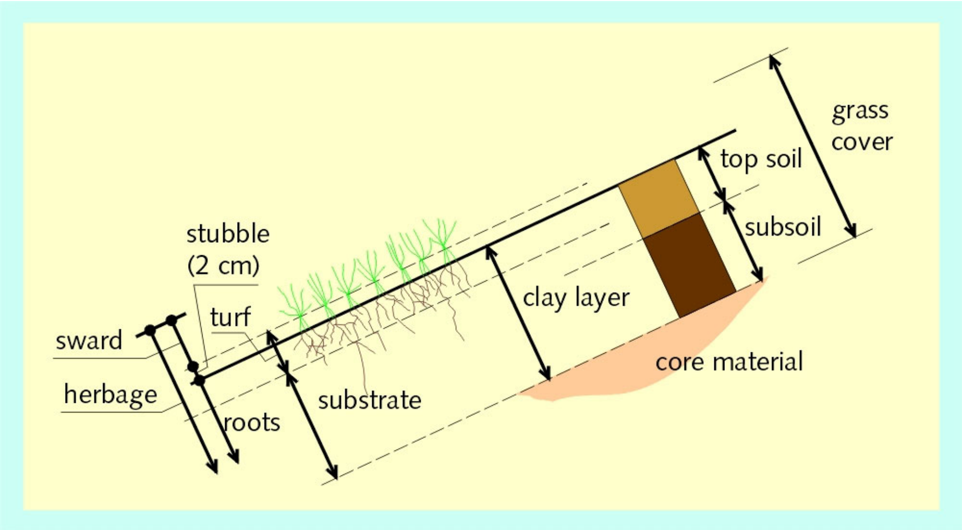


Figure 3.1 Structure and division of a grass cover (Source: Rijkswaterstaat)

The soil in sod consists of small and larger particles, so-called 'structural elements', between which are found pores and roots. Particles smaller than 20 μm are united into larger particles and these form larger pieces until an aggregate of several centimetres is formed. The particles are formed due to changes in the ground level of the surface, by ice formation, burrowing animals and sod penetration. They can also be formed by 'cementing' material sticking particles together. Plant roots and especially the chemical processes in the immediate neighbourhood of the roots are important for the existence of these 'cementing' materials.

The plant roots are themselves also an important item in keeping the particles in the soil together (Figure 3.2). The very fine root hairs and symbiotic fungal threads in the soil keep the fine aggregate together because they are anchored within the substrate. The coarser plant roots keep large and small particles together in a sort of network. This network of fine and coarse roots makes the sod a strong, springy and flexible layer, that can deform without tearing. It is also very water-permeable, which gives the water very little to hold onto and therefore cause erosion.

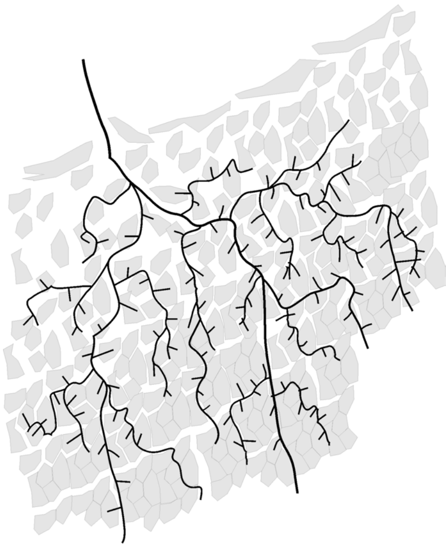
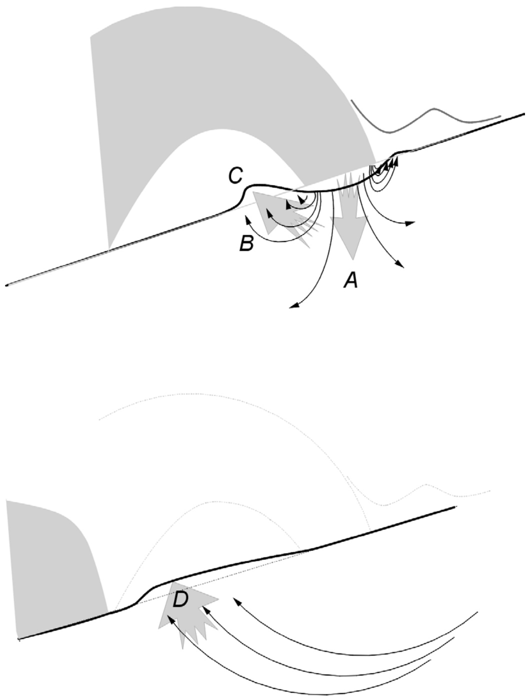


Figure 3.2 The structure of the turf (Source: GeoDelft)

Explanation: The network of roots, sometimes more than 1 m per cm^3 of the turf, is important for keeping the soil together (soil reinforcement), but at least as important is the structure of the soil in between the roots. Both effects contribute to the erosion resistance of the grass cover.



A: compression by wave impact

B: water flow away from impact zone

C: sideways and upward movement of soil adjacent to impact

D; sideways and upward movement upon withdrawal of wave

Figure 3.3 Waterflow through the soil and movement upon wave attack (source: GeoDelft)

The protective nature of sod rests on two characteristics that each play a role at a certain loading level from waves:

- *flexibility and springiness of sod*. This works against the loading caused by wave impact. Due to the power by which the impact of high waves is linked to the water pressure in the ground, part of the dike bank can become unstable, especially below the calm water line during and after a wave attack. The flexibility and the springiness of the sod keep the ground together. From tests and calculations, it appears that the springiness of the sod is sufficient to protect clay banks that would otherwise (without grass) erode very quickly.
- *retention of soil particles by root network.* This works against the wave effect on the bank, i.e., in zones with wave run-up and run-off. Individual soil particles, as in sandy ground, are swept away by the water flow if they are not adequately stuck together by these 'cement' connections. In addition, the plant parts above the ground can limit the interaction between the moving water and the soil.

3.2.2. Vertical structure of sod

Sod has a vertical succession of depth zones and how these zones lie depends on the soil type and the type and age of the vegetation. For well-rooted sod, the structure is as follows:

- The uppermost layer of 1 to 35 mm consists of loose soil and plant remains; this layer is washed away very quickly by waves.
- Immediately below is a layer 5 to 50 mm thick in which the sod is loosely packed and usually closely rooted; this layer is only slowly eroded away.
- Under this is a layer between 5 and 15 cm thick in which the sod is often more closely packed and the number of roots is considerably less; this zone is only attacked after a very long period of wave loading.
- Further below, the number of roots decreases and the soil is more closely packed.

This vertical structure can show substantial differences over quite short distances, and horizontally the structure of these vertical zones can differ significantly over a few metres, both as a consequence of local differences in the interaction between the plant roots, soil animals and the soil itself.

3.3. Large-scale laboratory studies

Two modelling studies have been done at full scale on grass banks: the first[1] was a test with relatively low ($H_s = 0.3$ m) waves on a number of sod samples of grassland banks taken from the upper Large Rivers area. The second test[2] used higher ($H_s \leq 1.35$ m) waves on sod taken from the Friesland Wadden Sea dike.

3.3.1. Scheldebak test 1994

The test with low waves was intended to determine, for the various types of grassland, what anti-erosion strength is necessary to be able to withstand a certain level of wave loading without noticeable damage. The typical conditions were a wave height of 0.3 m with an interval of 2.5 s, and a duration for wave loading of 60 hours; the sod was built on a bank of slope 1:3. The manner and amount of erosion were determined by measurements and by visual inspection, and the composition and structure of the vegetation and soil were determined.

Various river dike grassland types maintained by a variety of management conditions were tested. The grass mats were in Spring condition. Strong sandy soils and those intensively fertilised were not tested. The tests showed that:

- after many hours of loading, erosion of well rooted sod had removed only the uppermost few centimetres of soil;
- more than 0.1 m of soil was removed from a bank with a very moderately rooted sod;
- in areas where sod was almost absent from the bank, holes of more than 0.2 m deep appeared very quickly.

The damage to the grass and soil occurred mainly in the zone in which the waves were breaking. In the wave run-up zone, clear erosion also occurred and the plant cover was damaged.

Mole and mouse holes did not appear to have any noticeable influence on the erosion, except in places where there was a strong root network in the sod. Holes made expressly in the grass mat and about the size of a paving stone had not become larger after 12 hours of wave loading.

The composition of soil in the sod showed a great deal of change depending on its position.

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[1] Scheldebak, Delft Hydraulics Laboratory, 1994.
[2] Deltagoot, Delft Hydraulics Laboratory, 1992.

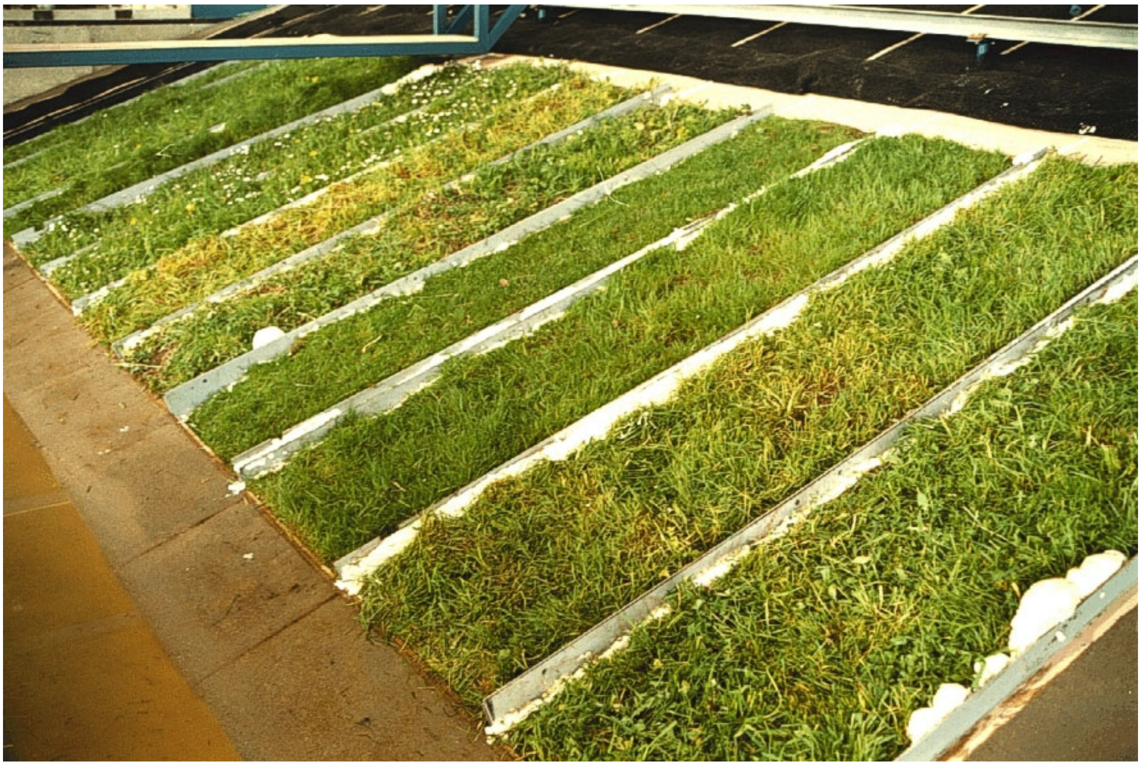


Figure 3.4 Large scale tests on the turf from the riverdikes (Source: Delft Hydraulics)

Most of the soil from the sod samples studied could be categorised as *good erosion-resistant* [TAW, 1996]. Two locations fell into the categories *little erosion-resistance and moderate erosion resistance*, according to this classification of untreated clay for dikes without vegetation. The observed amount of erosion was dominated by the quality of the root system and not by the type of soil in the sod. Well-rooted sod was almost never obviously eroded, except that for two sod samples, one with little erosion-resistant clay showed a larger amount of erosion than one with moderate to good erosion-resistant clay. The greatest erosion was observed for sod with a good erosion-resistant clay, but with a poor rooting system, as a consequence of a management type in the form of rough mowing.

It can be concluded that a good rooting system in the sod is decisive in determining erosion resistance, whereas the erosion-resistance category of the clay is no longer of importance. These findings agree with field observations of 0.4 m waves along a sea dike in Zeeland-Vlaanders, in which damage of several decimetres deep was seen in a very poorly developed sod in 48 hours, despite a moderate to good erosion-resistant soil.

3.3.2. Deltagoot test 1992

A sea dike was used for testing a grass mat with higher waves: the grass mat was placed against a bank with a 1:4 slope and was loaded with waves of 0.75 and 1.35, with wave intervals of 3.4 and 4.7 s, respectively, for a duration of more than one day. It was intended to determine the erosion of the sod as a function of the wave conditions, and to prepare an analysis of the erosion process to gain more knowledge of the relationship between load and strength. Visual observations of the erosion were made and measurements were made on the bank, together with measurements of water movement and water pressure on and in the bank, and the deformation of the soil. Observations of the consequences for the inner bank of water run-off after wave over-topping volumes of 0.1 to 25 l/s per metre showed that no erosion of the sod occurred.

Figure 3.5 Erosion hole after 11 hours of wave attack during large scale test with the turf from the seadike (Source: Delft Hydraulics)

The tested grass mat had been moderately fertilised and relatively strongly grazed. A sod with a species-poor vegetation, that was evaluated as poorly erosion-resistant, could even withstand high waves for a very long time. The sod had relatively good sod penetration in erosion-resistant soil and, with waves of 0.75 m during more than one day, it did not collapse. The grass layer did get badly damaged, but the sod had only lost the top few centimetres of soil. The sod collapsed after about 16 hours of loading with waves of almost 1.4 m high. After about six hours, a small hole appeared, but it only grew larger slowly.

Based on species composition, the tested grass mats were categorised into the usually considered to be low-erosion-resistant Rye-grass meadow. This conflict can be resolved as follows: the sod originated from an old dike, in which it had developed a close root network. In the past 10 years, the dike had been more intensively fertilised and grazed, such that a floral decline had occurred. A time-lag effect was also apparent from the previous situation, which is characteristic for a type with more erosion resistance (Crested dog's tail pasture). This shows that the history of a sod is also a factor in determining its erosion resistance.

During part of the test, the water pressure in the clay layer under the sod was measured. This water pressure is an important factor for the power that causes erosion, especially for higher waves. The registered water pressures were often high enough to move soil upwards from the bank. Calculations which included the water pressure in the undersoil and the direct wave loading on the bank showed that only a strong and springy sod prevented erosion of the bank. This conclusion was confirmed by similar tests with high waves on banks with clay with no or very poor sod penetration. Tests on sod and undersoil were performed in order to obtain quantitative data *in situ* and in the laboratory. Very large samples were used to take into account variations within the sod and soil structure.

3.4. Botanical composition and erosion resistance of grassland

The plant communities, type of grassland management, soil composition, sod penetration and erosion resistance have been described for a large number of river and sea dikes. On some samples of river dikes and on 20 samples of sea dikes, the type of management was changed to be able to follow the effect on the vegetation, sod penetration and erosion resistance over time. The relationships that were found are described in the following paragraphs, for each plant community. Table 3.1 shows a summary of the plant communities on river and sea dikes with mention of some characteristic species.

Table 3.1: Plant communities and characteristic species

PLANT COMMUNITY	CHARACTERISTIC SPECIES
Dry streamside valley grassland	Field Mouse-ear, Downy alpineoat grass, Mouseear hawkweed, Lemon thyme, Yellow Spring bedstraw, Thymeleaf sandwort, Burnet saxifrage, Field eryngo, Sickle Medick, Perennial quakinggrass, Meadow Clary , Sweet vernal grass
Oat-grass hay meadow	Hedge vetch, Meadow fescue, Rough hawksbeard, Smooth bedstraw/ False baby's breath, Tall buttercup
Crested dog's tail grass pasture	Smooth bedstraw, Timothy grass, Cinquefoil, Daisy, Self-heal, Small hawkbit, Jacob's cross, Crested dog's tail, Kingcup, Ground ivy
Oat-grass hay meadow with edge species	Leafy spurge, Wild marjoram, Cross-leaved bedstraw, Hairy ragwort, Rampion belflower
Rye grass meadow (production pasture)	English rye grass, Daisy, Wild geranium
Fallow pasture with tall herbs	Cow parsley, Goose grass, Meadow foxtail, Cow parsnip

Table 3.2 shows that most dikes have a less erosion-resistant grass mat, but this does not mean that the grass on the dikes is not strong enough. It does mean that at high water and depending on the loading from the waves, there is a greater chance of damage occurring and that earlier additional measures must be taken. On the dikes, the management has not been aimed at the protection and development of characteristic nature valuable for the dike.

3.4.1. Plant communities on river dikes

The species-rich communities on river dikes can be classified according to the following categories, in order of decreasing erosion resistance:

- Dry streamside valley grassland;
- Oat-grass hay meadow with and without edge species, for which management consists of

mowing once or twice a year with removal of cuttings while retaining fertilisation;

- Crested dog's tail pasture, managed by grazing without fertilisation.

Table 3.2: Plant communities on river dikes, and primary and secondary sea dikes (and including lake dikes)

TYPE	NO. SPECIES	EROSION RESISTANCE	%RIVER DIKE	%SEC. DIKE (LAKE DIKE)	% PRIM. SEA DIKE	MANAGEMENT
Streamside valley grassland	30	++	0.5-1			Unfertilised 1 x hay-making
Oat-grass hay meadow with edge species	27	+	0.1-0.3	5	0.05	Unfertilised irregular hay-making
Oat-grass hay meadow species-rich	32	++	2-4	1	0.05	Unfertilised 1 x hay-making
Oat-grass hay meadow species-poor	13	0		5	10	Fertilised hay-making
Fallow pasture with tall herbs	8-20	0	20-30	20	10	Heavily fertilised hay-making or rough mowing
Crested dog's tail pasture species-rich	36	++	2-4	1	0.5	Unfertilised grazing
Crested dog's tail pasture species-poor	15	+		15	20	Fertilised grazing
Rye grass meadow	12-18	0	60-70	50-55	60	Heavily fertilised grazing

The various communities that are found on river and sea dikes are given in Table 3.2 with the estimated percentage part that they occupy of the total area of river and sea dikes. The

occurrence of various plant communities is mainly dependent on the type of management followed and in a lesser degree on the soil type and general habitat factors. Dry streamside valley grassland has a limited distribution on relatively sandy soils. Oat-grass hay meadow and Crested dog's tail pasture are distributed throughout the Large Rivers area and have strongly decreased in surface area due to changes in management. Oat-grass hay meadow with edge species is found mainly in Zeeland on inner dikes. Approximately 70% of the area of dikes consists of a species-poor community: Rye grass meadow (production grazing) or Fallow pasture with tall herbs.
Dry streamside valley grassland, Oat-grass hay meadow and Crested dog's tail pasture have good erosion resistance because of their closed sod. They have a deeper and more intensive root system than Production grazing pasture and Fallow pasture with tall herbs. The least amounts of material were washed out in the field erosion test for Dry streamside valley grassland, Crested dog's tail pasture and Oat-grass hay meadow. There was no significant difference between the communities in the time required for the same loss of weight, according to the erosion centrifuge test. Production grazing pasture showed a relatively low erosion resistance, despite a good covering. This is the consequence of low root density, with the roots being almost exclusively in the top 10 cm of the soil. The percentage of samples that did not survive the erosion centrifuge test was highest with the Production grazing pasture.

Figure 3.6 Field measurements (Univ. of Wageningen)

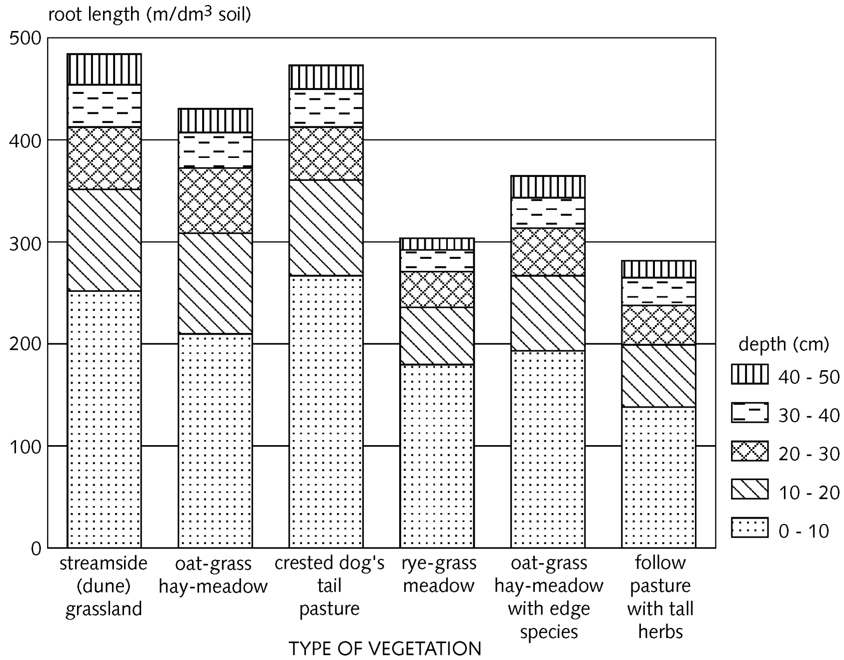


Figure 3.7 Average density of roots per specie type (Source: University of Wagenigen)

In the field erosion test, five to 20 times as much material was washed away from Fallow pasture with tall herbs than from the other managed pastures, because this type has a low root density and thereby a very open sod. In this field erosion test, the amount of material washed away depends on the density of the sod. Measured using the erosion centrifuge test, the erosion resistance depends on a combination of the root system and the distribution of soil particle sizes. It can be concluded that vegetation with a large richness in species copes very well against low waves such as in the Large Rivers area, and these dike grasslands are looked on as places of high natural value.

3.4.2. Plant communities on sea dikes

The species richness of sea dikes is almost always low as a consequence of fertilisation of grazing pasture and hay meadow. In areas that are not fertilised, species-rich Oat-grass hay meadow and Crested dog's tail pasture occur. On relatively sandy areas on sea dikes in the north of the country, a species-poor variant of Crested dog's tail pasture occurs that is not found on river dikes; the cover of Red fescue is high in this variant. On the sea dikes in Zeeland, a species-poor variant of Oat-grass hay meadow also occurs, with the vegetation often showing only a few grass species (Oat-grass, Red fescue, Couch grass, reed fescue, Cocksfoot) and other plants (Hogweed). This is fertilised hay meadow with such a high production that it must be harvested two or three times a year. Fallow pasture with tall herbs also occurs often on sea dikes, due to rough mowing. Most of the area has fertilised species-poor Rye grass meadow. The species-rich vegetation of Crested dog's tail pasture and Oat-grass hay meadow can be found sporadically on diagonals or locally on a secondary dike.

The unfertilised, species-rich communities are also the most erosion-resistant on sea dikes, according to an erosion centrifuge test in which the layers 0-5 cm and 5-10 cm were tested separately (Figure 3.8). In addition to this test, a field erosion test was performed and the resistance to shifting was measured, which showed no difference between unfertilised Oat-grass hay meadow and fertilised grasslands (species-poor Oat-grass hay meadow, species-poor Crested dog's tail pasture and Rye grass meadow).

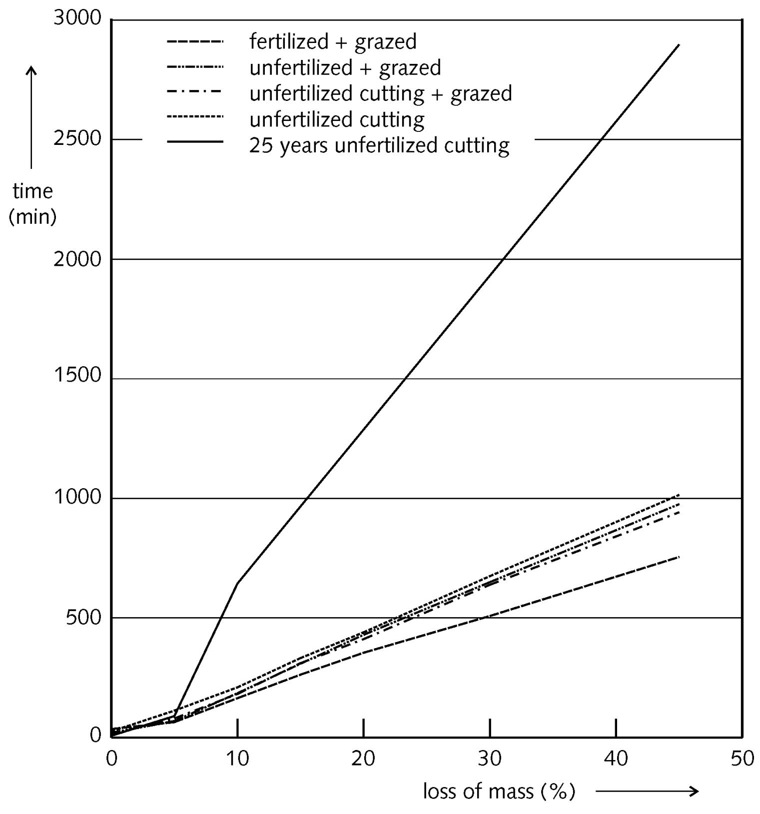


Figure 3.8a Erosion centrifuge test at depth 0-5 cm; relationship between the accumulated mass loss in % and the time period for various types of management

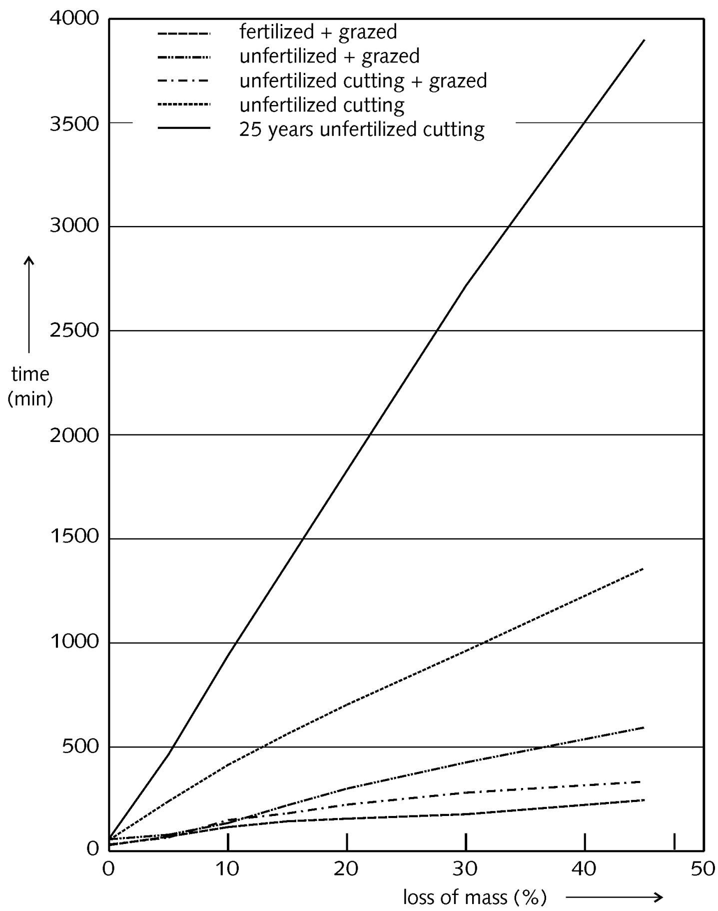


Figure 3.8b Erosion centrifuge test at depth 5-10 cm

As with river dikes, the most erosion-resistant type (species-rich Oat-grass hay meadow) has the highest root density with high values for root length and total root mass. A further indication that erosion resistance is provided by the roots is that these tested sod sample had a low covering of stems and leaves above the ground. In comparison, the fertilised Crested dog's tail pasture has limited resistance against erosion - it has a high covering above ground and a very shallow root system. Well-developed above-ground parts of plants (stems and leaves) have little influence on erosion resistance.

3.5. Test projects for construction and management

3.5.1. Fertilising, grazing and hay-making

Discontinuing fertilisation, less intensive grazing and hay-making once or twice a year all change the botanical composition and thus the root systems of sod, which improves the erosion resistance. An experiment in management by removal or not of cuttings has been performed on river dikes and, after three years, the amount of sod penetration had increased in the test areas with removal of cuttings. The amount of material washed out was therefore lower than in the test areas without removal of cuttings.

In the period 1991-1995, a series of experiments were performed on fertilised grazing pasture of sea dikes, in which fertilisation was discontinued and three management variations were started:

- two periods of grazing;
- hay-making once after grazing;
- hay-making twice.

The 'hay-making twice' variant showed an increase in sod penetration in the 6-10 cm layer, and it resulted in a relatively deep root package with thin and thick roots, just as in species-rich hay meadows. Shallow rooting species such as English rye grass and Common chickweed decreased, and closed rooting species, such as Red fescue increased. This experiment showed that the transition from fertilised farming to a non-fertilised natural type of management is favourable for erosion resistance even after a relatively short time.

3.5.2. Sowing

At Pannerden, there is a river bank sown with various mixtures of grasses at different densities, for which the applied management is mowing with removal of cuttings, and sheep grazing. It appears that the composition of the sown grass seed mixture determines the vegetation; after seven years, species from the sown mixture were dominant in all of the areas. The dominant role of the seeds that were there first, in the final composition of a newly developing grass covering, was also shown in an experiment in the test area of Zaltbommel. After making the dikes stronger, the effect of differences in construction and management was studied. The following factors were important for the recovery of species-rich erosion-resistant grassland:

- Returning the sod soil, originating from a species-rich grassland, in which there are many seeds from streamside valley species, so that they can re-establish themselves more quickly.
- Rapid development of erosion-resistant grassland is also initiated by sowing with a seed mixture that is recovered from places with a species-rich grassland. It is important that the seed is recovered at the time that most species have ripe seeds.
- Sowing with a grazing grass mixture (e.g., BG5) at high density (70 kg/ha) results in a poorly developed root system; this is not therefore recommended.
- Sowing with Italian rye grass (20-25 kg/ha) also results in a limited root system, because it is an annual plant. However, it is preferred above the BG-5 mixture, if commercial grass seed only is available. This grass fixes the upper soil but does not remain dominant and, therefore, streamside valley species can gradually take a hold.
- The management type 'mowing twice with removal of cuttings' results in a sod with the highest erosion resistance and the highest root density.
- Grazing results in lower erosion resistance due to the lower and shallower root density.

3.6. Experience during high water levels on the Large Rivers

Ten locations were selected in the upper Large Rivers area for gaining experience of the behaviour of grassland during high water levels, especially concerning erosion resistance [Heidemij, 1994]. In the reporting period of Spring 1991 - Spring 1994, only one high water period occurred by which the banks were under water. This was December 1993 until February 1994 with a peak around Christmas 1993. The wind speed was low, and in combination with length of wave impact, dike orientation, etc., waves of a maximum of 0.30 m resulted for a duration of less than 12 hours, and waves of a maximum of 0.20 m for a duration of more than 12 hours.
Clear damage was observed at a number of locations after the high water levels; however, some of the damage was caused by driftwood, with no relationship to the quality of the grassland. Other damage was caused by poorly rooted and fertilised sod, but the damage remained limited because the wave surge was limited. A heavier wave surge would have caused greater damage.

In the period January/February 1995 on the Rhine and Maas rivers, very high water levels occurred [TAW, 1995], together with an approximately force 5 SW wind that caused estimated wave heights of 0.15 m. Damage was caused at various places on the outer banks on the north-east side of the rivers, but this was not serious. The damage occurred at places where the grass mat had a poorly developed root system due to unfavourable management, e.g., the area Opijnen-Heesselt, along the Fraterwaard near Duisburg and the area Lent-Oosterhout. These results agree with those from the period December 1993 to February 1994.
Furthermore, small holes were observed resulting from driftwood impact, damage from lamp posts, or on sandy banks, where sometimes more than 0.15 m of soil had been eroded over a length of more than 100 m.
From studying the damage-test areas, it appears that the observed wave heights were considerably lower (about half) than those predicted using the wave-growth curves of Brettschneider, on which the wave impact length has a major influence. Only if an impact length is assumed that agrees with the distance to the dike of the last strong gradient of the rate of flow did the predicted wave height appear to be the same as the measured wave height. This means that the flow effects have a dampening effect on the height of the waves, but further study is required to be able to put these effects into numerical calculations.

4. Current status of models

A behaviour or damage model describes the relationship between load and strength and, for the studies performed, most attention was given to the strength of grassland as dike covering. Very little attention has been given to the loading. An integrated behaviour model that covers the complex relationships type of soil - vegetation - management - sod penetration - strength - loading is not yet available, although a start has been made.

The study results have led to a descriptive model and an empirical behaviour and damage model, and these models are discussed in the following paragraphs. We also look at a model by which the effect of wave loading on a combination of a number of erosion mechanisms can be predicted. Finally, the relationships between management and sod quality are discussed.

4.1. Descriptive model

On the basis of our current insights, derived from the above-described tests and practical situations, the following model has been established for the wave breaking zone[3]:

Wave height < 0.4 m

Rooting of grassmat	**Time**	**Effect**
Well-rooted grass mat	in 1-2 days	Very little sod erosion; even parts above ground remain intact
Very poorly rooted grass mat	Within a few hours	Holes up to to 0.4 m deep
SPECIAL SITUATION: Moderately well-rooted grass mat on very sandy soil	Sometimes within 1 day	Holes up to 0.3 m deep

Wave height 0.4 - 1.0 m

[3] For the other zones the load is less.

Well-rooted grass mat	in 1-2 days	Very limited erosion of sod; parts above ground severely damaged after 1 day
Poorly rooted grass mat, depending on top layer, underlayer and core	within 1.5 days	Holes up to more than several decimetres
Wave height 1.0 - 1.5 m		
Moderate to well-rooted grass mat	in 0.5-0.75 days	Sod collapsed
Poorly rooted grass mat, depending on top layer and undersoil	Within a few hours	Deep erosion
SPECIAL SITUATION grass mat with severe damage	Within a few hours	Bank severely damaged

Erosion is a progressive process. The total loading is a product of the duration and severity of the load. This is the reason why for river dikes, although the wave height will be much less than for sea dikes, the loading over a longer time can still be considerable.

River flow along an outer bank causes a lower loading than the 30 cm waves that caused no trouble to an erosion-resistant grass mat and therefore river flow contributes only slightly to the erosion load.

From large-scale tests [Klein Breteler and Smith, 1996] it appears that wave over-topping up to 10 l/s per metre results in very little erosion for the inner bank. The duration of the load is thereby always much less than on the outer bank. It can be concluded that a moderate to well-rooted grass mat can withstand this without damage.

4.1.1. Influence of bank slope

There has been no systematic study of the influence of the bank slope in the studies described. However, some remarks can be made from experience: the influence of a difference in bank slope is relatively limited in comparison to variations in the strength of the grass mat. For banks steeper than 1:2.5 the steepness does play a role considering that gravity weakens the grass mat,

especially for moderate and poor sod penetration. This effect must not be confused with the less convenient maintenance of grass on steep banks. On banks steeper than 1:2.5 (up to 1:1; steeper banks do not occur on dikes) it is possible to achieve a good grass mat by using special equipment for mowing. So-called 'sheep paths' can be seen on very steep banks, caused by 'creeping' (i.e.sliding of the soil), and this means a weakening of the cohesion (and thereby the strength) of the root layer.
On very flat banks (flatter than 1:5), Burger [1984] showed that the loading is reduced by an important amount because waves breaking on the bank are damped by a water layer that is still present on the bank from the previous wave. A directly proportional load correction with the deviation of the bank slope in relation to the studied slopes of 1:3 to 1:4 appears to be a good first approach to calculating the influence of the bank slope on erosion.

4.1.2. Part of bank with wave run-up and run--off

For sea and lake dikes, it is relevant to know what the grass mat can withstand in the area of the bank with wave run-up and run-off as a result of waves breaking on a hard covering. The load on the grass mat will be less there than in the breaking zone. During the large-scale test in which this phenomenon was measured, with wave heights of 1.35 m, there was no damage in the run-up area. The rate of erosion above the calm water line was less than a quarter of that in the breaking zone, and decreased even further up. A greater allowed wave height compared to that in the breaking zone appears also to be justified, unless because of the design of the transition between the hard covering and the grass mat no magnification of the loading occurs. It is assumed that the erosion rate is directly proportional to the loading, which is in turn probably proportional to the wave height to the power of 1.5 to 2. With lower wave loading, the decrease in erosion rate is much less in the run-up zone compared to that in the breaking zone.

4.2. Empirical behaviour or damage model

Using the results of large-scale laboratory tests, a provisional empirical comparison was made between wave attack and erosion rate for sod. On theoretical grounds, it is supposed that the erosion rate increases as the square of the wave height, and that the effect of the quality of the sod can be expressed as a proportionality constant (Figure 4.1):

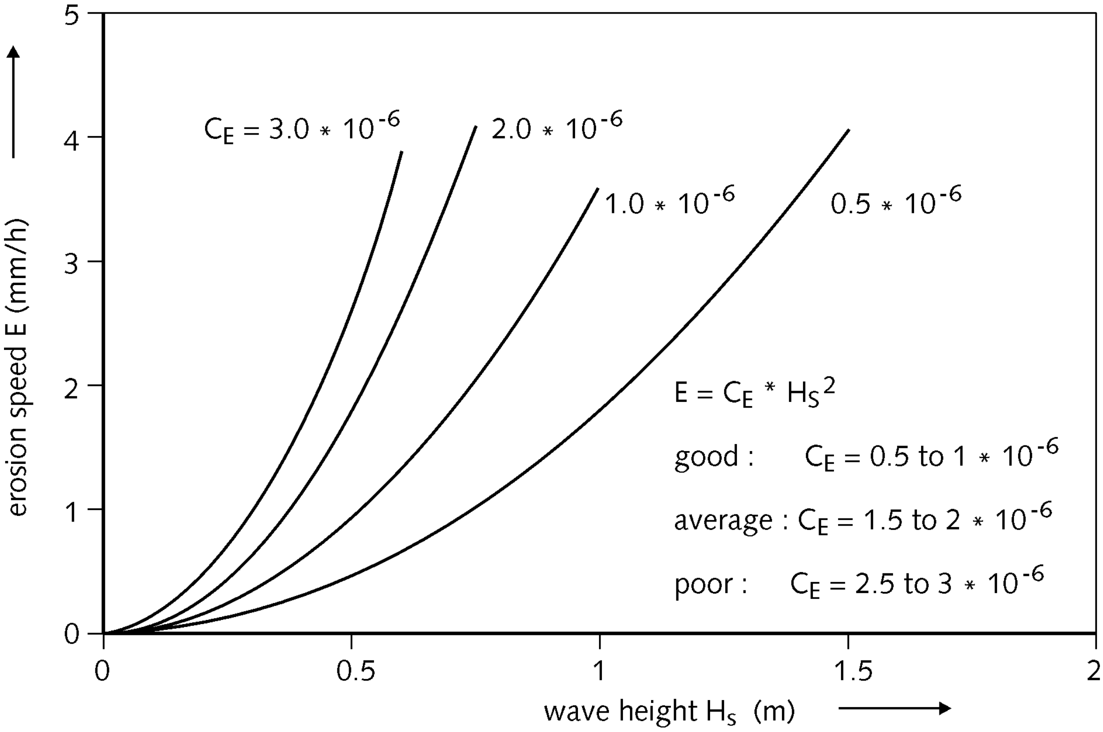


Figure 4.1 Rate of erosion versus wave height

$$E_{grass} = c_E H_s^2$$

where E_{grass} = erosion rate (m/s)

c_E = grass erosion coefficient ($m^{-1}s^{-1}$)

H_s = significant wave height (m)

From the results of the large-scale tests, the following conservative classification can be proposed for the coefficient c_E:

Erosion-resistant grassland	Expected values for c_E
Good	0.5 to $1.5.10^{-6}$ $m^{-1}s^{-1}$
Moderate	1.5 to $2.5.10^{-6}$ $m^{-1}s^{-1}$
Poor	2.5 to $3.5.10^{-6}$ $m^{-1}s^{-1}$

This relationship can rather simply be translated into a permitted duration of wave loading for a certain wave height, and thickness and level of erosion resistance of the sod:

$$t_{max} = d/(\gamma \, c_E \, H_s^2)$$

where t_{max} = maximum permitted duration of loading (s)

d = sod thickness (m)

γ = safety coefficient (-)

Tests made in England which studied the load caused by flooding water on grassland (Hewlett et al., 1987) support this relationship.

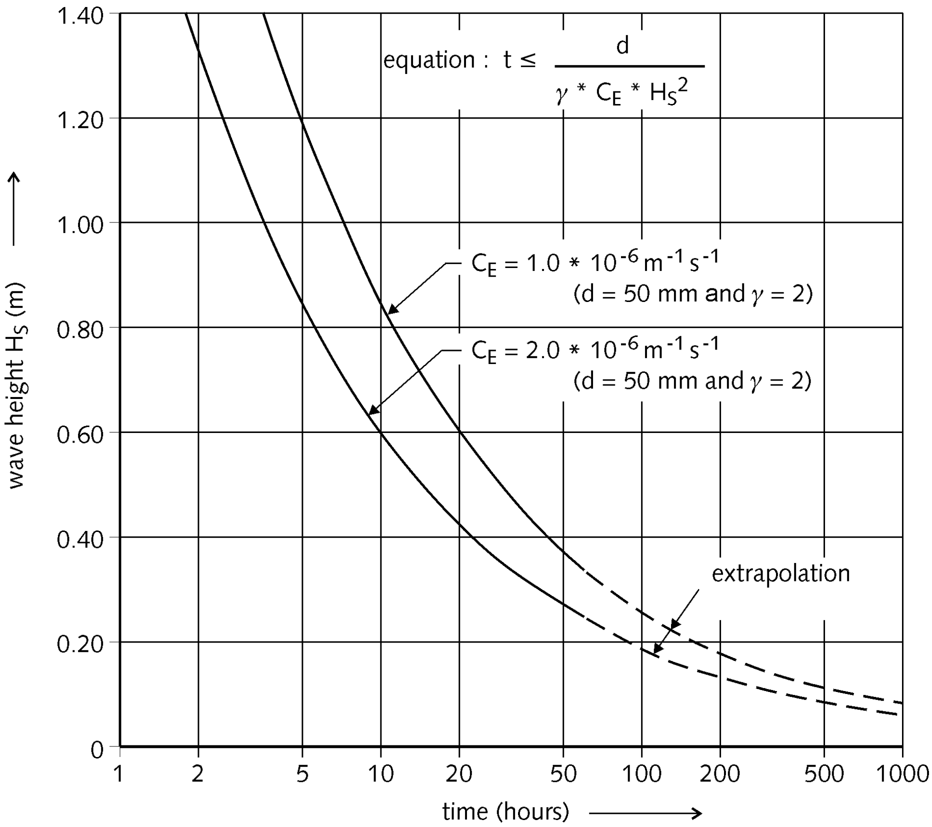


Figure 4.2 Maximum permissible duration of wave attack (Source: Delft Hydraulics)

Attempts have been made to relate the grass erosion coefficient to the quality of the sod penetration and of the soil between the roots. The relevant parameters are root density, root length, and the content of fine soil particles that can be washed out. The test results do not give any clear figures. It also did not appear to be possible to include any influence of the wave interval (or wave steepness) or bank slope into the above relationships. The distinguishing power of the tests was therefore too limiting (from 2.5 s for H_s = 0.30 m and bank slope 1:3 through 3.4 s for H_s = 0.75 m and bank slope 1:4 to 4.7 s for H_s = 1.35 m and bank slope 1:3). There is as yet no clarity in the figures for relevant, simple and measurable parameters.
Furthermore, the meaning of the results of the small-scale field erosion tests using a spray head, and laboratory tests using the erosion centrifuge equipment is also unclear. The sea dike study did show from the centrifuge test that there was a clear difference in erosion resistance between long duration unfertilised hay meadows with high root density and fertilised grazing pasture with low root density.

In summary, it has been established that the empirical model still contains some uncertainties concerning application area and accuracy, which means that it cannot yet be used in practical design work.

It is possible to improve the model by distinguishing the following sub-processes of erosion in sod:

(a) washing away of loose soil particles and lumps;
(b) collapse of (hair) roots that keep the soil particles and lumps together;
(c) complete or partial tearing, or breaking open of sod.

Indications are available of the level in which the various sub-processes behave in relation to the wave height and the quality of the sod. Separation of the loading and strength is possible using this approach and the effects of density and strength roots, soil, bank and wave loading parameters can be modelled independently. For example, it is also possible to examine the influence of the bank slope, or of different types of sod penetration, such as effectiveness of the somewhat less sod penetration deeper in the soil, the effectiveness of a thin, just laid sod, the difference between a sod with many thin roots and a less dense sod with somewhat thicker roots.

For the time being, this model serves to improve our insights. The current version of the model accepts the fact that loose small soil particles and lumps are washed out of the soil surface by waves a few decimetres high. Roots can keep soil lumps together for a long time and severe erosion of the sod will not then occur. For waves higher than just a few decimetres, severe erosion will take place with an open root network, but with a closed root network (reasonable to good quality sod) the roots are sufficiently strong to withstand waves of up to 0.75 m. The sod is lifted up and stretched many millimetres by each break of waves higher than about 1 m. The roots in the sod are weakened over time by these relatively severe movements between the soil particles.

The strength of (individual) grass roots and the complete sod must be studied further in order to broaden the application and validity of this model, using data from published reports, strength calculations and experiments. The amount by which loose soil lumps can be washed away also needs to be quantitatively determined, and further analysis of the data from the various tests is necessary.

4.3 Working out a loading model

Very little attention has been given to a loading model. A study in England used water flow rates as the loading parameter [Hewlett et al, 1987]. During the tests on wave loading described in this report, wave height, wave interval, wave run-up, water layer thickness and water flow rate were measured. Water flow rates from waves on a bank can be predicted using the normal formulas derived from civil engineering coverings [Meijer et al., 1994]. At this time, it is not easy to translate the wave loading from irregularly breaking waves into water flow rates or shearing forces.

A reduction coefficient for wave run-up as a consequence of the roughness of the bank compared to a smooth bank can be determined as 0.55 to 0.65 for small waves to 0.9 to 1.0 for the larger waves. Further analysis shows that for waves smaller than 0.75 m, the reduction coefficient appears to depend on the wave height thus:

$r = 1.15\ H_s^{0.5}$

where r is the reduction coefficient, and H_s is the significant wave height.

This is in regard to the more limited water layer depth from smaller wave heights and consequently relatively greater hydraulic roughness. In other words: with lower wave heights, the waves are lower with respect to the vegetation.

4.4 Relationships between sod quality and management

Despite the uncertainties in the empirical model, a relationship can still be shown between the type of management and the quality of the sod.

4.4.1. Density of sod

The tests showed that the erosion resistance characteristics of grass covering on dikes is determined by the soil in combination with sod density. The most important part of the sod is the root system, which forms the most prominent resistance against wave attack. The above-ground part of the sod (stems and leaves) contributes mainly to resistance against water run-off, thus for wave over-topping on the inner bank. An erosion-resistant grass mat shows soil and sod density that conforms to certain minimum requirements.

The uppermost 0.15 m layer develops completely different soil composition characteristics to the original soil, and in which an erosion-resistant root layer can develop and no erosion-resistant clay is required. A sandy clay will also be adequate as long as it has some cohesion. A sand content of maximum 50% appears to be a practical and sufficiently safe limit. Most Dutch clay types adequately comply to these requirements naturally.

The information above seems to contradict the requirements for clay on dikes as formulated in the Technical Report - Clay for Dikes [TAW, 1996]. There are thus the following two limitations for erosion-resistant clay:

- A good erosion-resistant grass mat is more erosion-resistant than the most erosion-resistant clay (category 1 according to the above-mentioned Technical Report [TAW, 1996]). The strength of the sod develops faster and better on sandy clay than on pure, unmixed clay. Considering that a grass mat always remains susceptible to choking up or mechanical damage, the erosion resistance of an underlying clay layer can be important for the safety of the dike as a whole if the grass mat becomes damaged.
- Erosion-resistant clay (category 1) over time loses its erosion resistance in the uppermost

decimetres as a result of chemical and physical processes ('structure formation'), by which cracking and crumbling occur. A sod can take on this role. After laying or recovery, grassland requires a few seasons to develop into a strong sod. Directly after laying or recovery an erosion-resistant clay can, at least in the first winter, ensure sufficient erosion resistance.

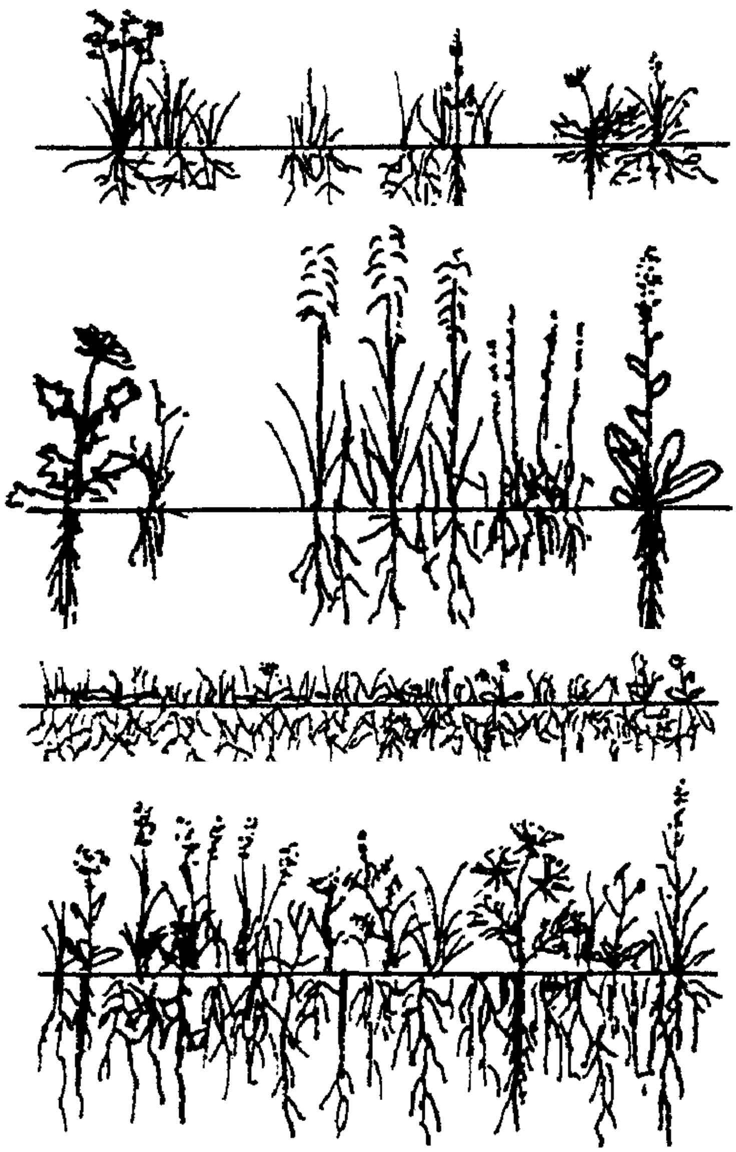
If a covering of erosion-resistant clay is selected for dike construction or reinforcement, the application of a top layer of sandy clay is recommended to ensure better development of the grass mat. The weakness during the first season, as mentioned, can be overcome by keeping the erosion-resistant clay closed and working it smooth, in order to add the top layer of sandy clay in the Spring. This does remove the problem that the new grass mat will in all cases remain relatively vulnerable for a few seasons.

4.4.2. Influence of type of management

The density of the above-ground vegetation and roots are both directly influenced by the type of grassland management. The types of management defined by Fliervoet [1992] from hydraulic aspects for sufficiently closed and well-rooted grass mats on river dikes (hydraulic, adapted farming, and natural management) are a good basis. From the earlier-described botanical study [Sprangers, 1996] these types of management can be specified as follows, in which the amount of fertiliser and the level of maintenance are critical factors:

- *Hay-making without fertilisation (hydraulic management and natural management)* produces the highest root density (closed root package with especially in the top layer up to 0.15 m deep many thick and thin roots), with a reasonably closed vegetation (Figure 4.3d). The natural value of the grassland can be highest with this type of management. Grazing with fertilisation can also be worthwhile, but hay-making is more practical, considering that no cattle grids, drinking-water facilities and other accompanying required maintenance are necessary.
- With *sheep grazing and light fertilisation (adapted farming management)* a good close sod forms, but the sod penetration (closed root package with many thin roots) is mainly developed in the uppermost 0-10 cm of the soil (Figure 4.3c). From the hydraulic aspect, this type of management is adequate. This type of sheep grazing requires an accurate

management plan based on the local situation, with the grazing not aimed after all at sheep rearing but on an erosion-resistant grass mat. The animal density must then agree exactly with the rate of crop production so that the whole area does not lose all its grass. Periods of several weeks of intensive grazing must be interspersed with rest periods, for among other things the seeding of grasses and other plants. This means constant moving of the sheep to other sections. The grass must start the winter short (up to 10 cm) and then not be grazed until the following Spring. Additional maintenance is required to mow off ungrazed patches and rough areas and to smooth out molehills.



4.3a grazing + fertilizing + herbicide use

4.3b cutting + fertilizing or rough mowing without removal

4.3c grazing = light (little) fertilization

4.3d cutting without fertilization

Figure 4.3 a to d Types of grassland for various maintenance strategies (Univ. of Wageningen)

- *Intensive fertilisation with grazing or hay-making* leads in general to a vegetation with open patches with low root density (Figures 4.3a and 4.3b).
- Twice a year *rough mowing and leaving the cuttings* leads to open patches and therefore to a low erosion-resistant sod.
- With *lawn management* (mowing seven to eight times per year) the cuttings remain lying; however, because mowing occurs so frequently the amount of cuttings per mowing remains limited. The root system forms a closed, shallow root package, concentrated in the uppermost 5 cm.

4.4.3. Sod quality as a function of type of management and sod density

Table 4.1 shows some types of management and the resulting sod density categories, translated into sod qualities of 'good', 'moderate' or 'poor'. The last category has shown erosion damage in practice on both river dikes (high water 1995) and sea dikes (February 1990).

Tabel 4.1: Sod quality as a function of type of management and sod density

TYPE OF MANAGEMENT	SOD DENSITY	SOD PENETRATION	SOD QUALITY
Hay-making without fertilisation	Covering > 70% open patches < 2 cm^2	Many thick and thin roots in 0-15 cm layer	good
Grazing with max. 75 kg N/ha fertilisation	Covering > 85% open patches < 2 cm^2	Many thin roots in 0-8 cm layer	good
Grazing with 75-100 kg N/ha fertilisation	Covering > 85% open patches 2-5 cm^2	Many thin roots in 0-5 cm layer	moderate
Lawn management (mowing 7-8 times a year) No fertilisation	Covering > 85% open patches > 2-5 cm^2	Many thin roots in 0-5 cm layer	moderate
Grazing with > 100 kg N/ha fertilisation	Covering > 85% open patches > 5 cm^2	Few thin and some thick roots in 0-5 cm layer	poor
Hay-making with fertilisation	Covering < 60% open patches > 5 cm^2	Some thick roots in 0-15 cm layer	poor
Mowing without cuttings removal	Covering < 60% open patches > 5 cm^2	Some thick roots in 0-15 cm layer	poor

Appendix 1
Summary of activities dealing with grass erosion

Studies on grass on dikes have been made since about 1970, starting with the run-off tests on the Knardijk, over a summer dike in Gelderland and in storm drains on small cut-sod samples. Since 1990, there have been more systematic studies of grass covering for dikes, for which the Grass Plan 1990 formed the guidelines. Under the auspices of the TAW-A3 *Project group 'Grassland as dike covering'*, the following activities have taken place:

1986-1996	Research study of sowing experiment on a dike at Pannerden. [Fliervoet, 1996]
1987-1996	Management test on the Great Maas and Waal (Zaltbommel): Effects of different methods of construction and management of grassland during and after dike reinforcement. [Liebrand, 1996]
1988-1992	Botanical composition and erosion resistance of river dikes. [Van der Zee, 1992]
1990-1991	Source research into the structure of the soil in sod and considerations on erosion processes for sod soil, including a limited laboratory experiment on permeability and erosion processes in sod, with descriptions of tested sod samples. [van Essen, 1994] [Kruse, 1993]
1990	Water movement on grass dikes from wave attack: theoretical study into wave run-up, rate of water flow and roughness of grassland. [Meijer et al., 1993]
1991-1996	Study of extensive grassland management on sea dikes: effects on vegetation, sod penetration and erosion resistance. [Sprangers, 1996]
10992	Brochure *'Construction and management of grassland on river dikes'*. [Fliervoet, 1992]
1992-1996	Deltagoot test of grassland bank on sea dike with slope1:4 (1992): measurements of effects of wave loading in and on the bank and observations of damage to grass and erosion processes, including wave over-topping of the inner bank. [Kruse, 1994a] [Kruse,1994b] [Kruse, 1996] [Smith, 1993] [Meijer, 1994]
1992-1994	Damaged test areas on river dikes: inventory of damage after a high water level. [Heidemij, 1994]
1993-1995	Observations of the condition and damage to sod on river dike banks by waves

during and after very high water levels. [TAW, 1994] [TAW, 1995]

1994-1995 Scheldebak test on river dike sod (1994): Large-scale comparative study into damage development on river dike sod, relationships between washing away of soil, soil composition and vegetation. [Verheij et al., 1995]

1990-1996 Setting up of Technical Report 'Clay for Dikes' by TAW-B6 project group. Formally, this was under a different research programme, but the results have still been included in the models and recommendations in the current report.

permanent Contribute to *Monitoring Guide*: establishing method for evaluation of existing grass coverings under extreme conditions.

The most important studies previous to this series were::

- wave simulation tests with sea dike sod in the flow channel at Lith in 1983 [van Meerendonk, 1984];
- Deltagoot test on a sod from a sea dike with a 1:8 bank in 1984 [Burger, 1984];
- study into clay for dikes [Kruse, 1988], and the wave channel tests at Delft Technical University with sod from river dikes [Wolffenbuttel, 1989];
- study of river dike vegetation [Sykora and Liebrand, 1987] and sea dike vegetation [Sprangers, 1989].

In addition to large-scale study material, research studies have also made use of the erosion centrifuge, in which water flows past a sod sample, and a field erosion test, in which the amount of material washed away was determined. In some studies, the shifting resistance was also determined as a possible measure for erosion resistance, but this provided no results.

Appendix 2

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Appendix 3

List of Dutch plant communities; names of species

Dutch name	Scientific name	English name
Akkerdistel	Cirsium arvense	Creeping Thistle
Akkerhoornbloem	Cerastium arvense	Field Mouse-ear Chickweed
Beemdlangbloem	Festuca pratensis	Meadow Fescue
Brunel	Prunella vulgaris	Self-heal
Echte kruisdistel	Eryngium campestris	Field Eryngo
Engels raaigras	Lolium perenne	Perennial Rye-grass
Fluitenkruid	Anthriscus sylvestris	Cow Parsley
Geel walstro	Galium verum	Yellow Bedstraw
Gewone berenklauw	Heracleum sphondylium	Cow Parsnip
Gewone zandmuur	Arenaria serpyllifolia	Thymeleaf Sandwort
Gewoon herderstasje	Capsella bursa-pastoris	Sheperd's Purse
Gewoon reukgras	Anthoxanthum odoratum	Sweet Vernal Grass
Glad walstro	Galium mollugo	Hedge Bedstraw
Grote brandnetel	Urtica dioica	Stinging Nettle
Grote streepzaad	Crepis biennis	Rough Hawk's-beard
Grote tijm	Thymus pulegioides	Broad-leaved Thyme
Grote vossenstaart	Alopecurus pratensis	Meadow Foxtail
Heggewikke	Vicia sepium	Bush Vetch
Heksenmelk	Euphorbia esula	Leafy Spurge
Hondsdraf	Glechoma hederacea	Ground-ivy
Jakobskruiskruid	Senecio jacobaea	Ragwort
Kamgras	Cynosurus cristatus	Crested Dog's-tail
Kleefkruid	Galium aparine	Goosegrass
Kleine bevernel	Pimpinella saxifraga	Burnet Saxifrage
Kleine leeuwentand	Leontodon saxatilis	Lesser Hawkbit
Knolboterbloem	Ranunculus bulbosus	Bulbous Buttercup
Kruisbladwalstro	Cruciata laevipes	Crosswort
Madeliefje	Bellis perennis	Daisy
Muizenoor	Hieracium pilosella	Mouse-ear hawkweed
Rapunzelklokje	Campanula rapunculus	Rampion
Ridderzuring	Rumex obtusifolius	Roud-leaved Dock
Rood zwenkgras	Festuca rubra	Red Fescue
Scherpe boterbloem	Ranunculus acris	Maedow buttercup
Slikkelklaver	Medicago falcata	Sickle Medick
Straatgras	Poa annua	Annual Meadow-grass
Timoteegras	Phleum pratensis	Timothy
Trilgras	Briza media	Quaking-grass
Veldsalie	Salvia pratensis	Meadow clary
Vijfvingerkruid	Potentilla reptans	Cinquefoil
Viltig kruiskruid	Senecio erucifolius	Hoary groundsel
Vogelmuur	Stellaria media	Chickweed
Wilde marjolein	Origanum vulgare	Wild Marjoram
Zachte haver	Avenula pubescens	Hairy Oat-grass
Zachte ooievaarsbek	Geranium molle	Dove's-foot Crane's-bill

General information

In 1965, the Netherlands Technical Advisory Committee for Flood Defence (TAW) was inaugurated by the Minister for Transport, Public Works and Water Management. This committee was established as a reaction on the flooding of part of the city of Amsterdam as a result of a dike failure.

TAW is now functioning for almost 4 decades. Its tasks have remained the same, namely:

- giving the Dutch Minister of Transport, Public Works and Water Management (asked or on own initiative) advice on matters concerning safety against flooding;
- preparing handbooks and technical reports for the dike managers (water boards), and;
- overall guidance of the ever needed research (on technical aspects of water defences as well as on the technical background of the safety approach).

To realise these tasks, the committee consists of representatives of the three governments that play a role in water defences (State, Provinces and Water Boards), and specialists from universities and private enterprise. An independent chairman and secretary at the water policy directorate of the ministry complete the TAW. TAW is advised by four committees: Technical affairs, Safety matters, River systems, Coastal systems.
TAW does not have an own budget; the Road and Hydraulic Engineering Institute from the Ministry carries out the work.

For questions on TAW's activities please contact the Road and Hydraulics Engineering Institute (DWW) of the Directorate-General for Public Works and Water Management.:

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