CHAPTER 124

RESISTANCE OF GRASSMAT TO WAVE ATTACK

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1. SUMMARY

The Dutch dikes along the North Sea and the tidal inlets need protection against erosion by wave attack. In 1983 two tests on full scale were carried out, concerning the resistance of large grass sods taken from Dutch sea-dikes, against wave attack.

For both tests in two different ways grass sods of 7500 to 9000 kg were dug from se-dike slopes, transported and placed in test facilities. In Test 1. the hydraulic load was performed by irregular waves up to H_s = 1.85 m, in Test 2. the hydraulic load was a simulated regular wave run-up with velocities until 4 m/s. Test 1. affirmed the possibility of a grassmat to withstand a design storm surge on a dike slope of 1:8 without severe damage. Test 2. showed the limits of erosion resistance and affirmed that the erosion resistance of a grassmat on sandy clay is concentrated in the upper layer of soil and roots.

2. TEST 1.

2.1 The motive of Test 1.

As a part of the realization of the so called Deltaworks in the Netherlands a section of 12 kilometers of the Frisian sea-dike in the northern part of the country should be enlarged (fig. 1).

The dike is situated on the south eastern side of the Waddenzee, a tidal flat of at medium 0.5 to 1 m below Ordnance Datum (O.D.) and a semi-diurnal tidal rise of about 2 m. The foreshore of the dike is a marsh situated about 1.5 m above O.D., that is some decimeters above

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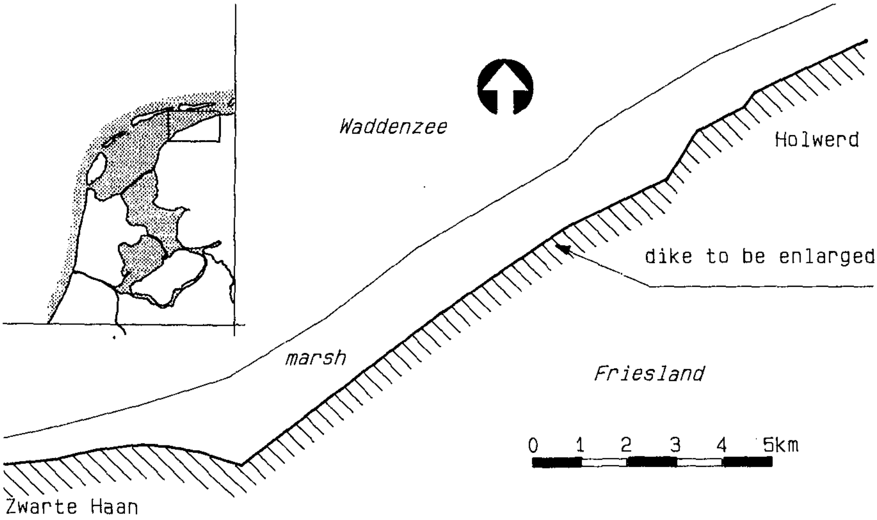

Figure 1. Plan of the Frisian sea-dike to be enlarged

the normal spring tide. Therefore only at storm surge tide a hydraulic load attacks the dike. The design water level is O.D. + 5.50 m, 1.80 m higher than the highest level that appeared in the past, with according wind waves of height H_s = 1.85 m, much higher than experienced in situ. The enlarged dike was designed with a relative flat outer slope from 1 : 12 up to 1 : 8 at design water level. Such a wide and rather voluminous cross section was possible because of the local available amount of clay as building material (fig. 2). This raised the question whether or not a non-reinforced grass revetment could be sufficient for the future.

Under design conditions the erosive effect of breaking wind waves will be the representative event. In the large wave flume of Delft Hydraulics it is possible to generate

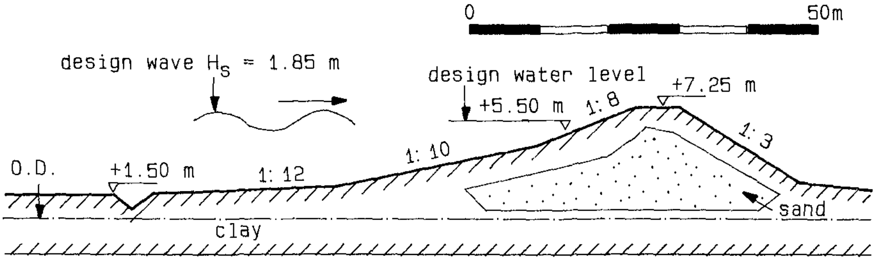

Figure 2. Cross section of enlarged dike

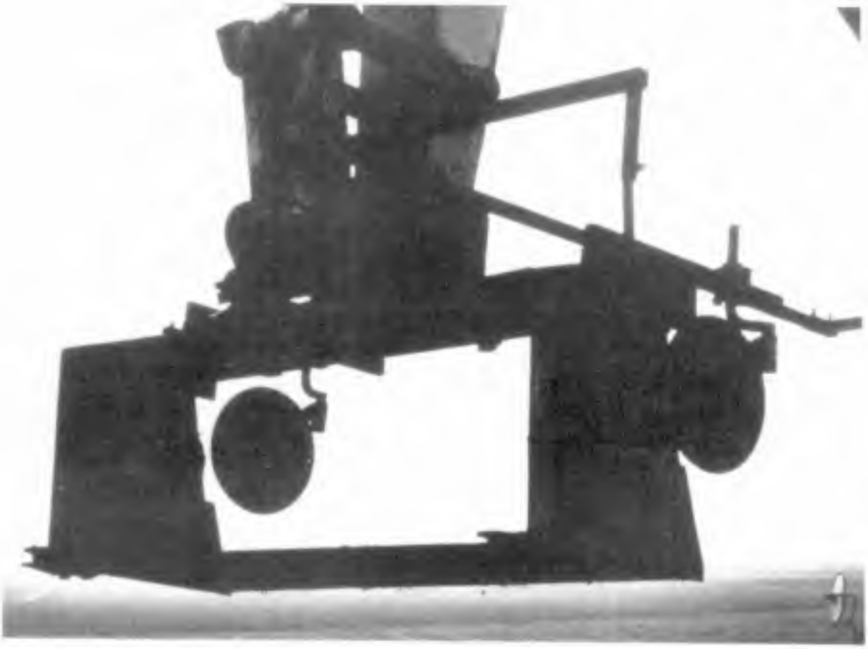

Figure 3. The sod cutting machine

Figure 4. A grass sod being transported

fully realistic the representative hydraulic load, related to water-level and irregular wind waves. The remaining question was the possibility of building a representative and full scale cross section of the outer slope and grass revetment.

2.2 Experimental set-up

As a representative grass revetment the grass of an outer slope angle from 1:5 to 1:6 of about ten years old at a comparable sea-dike was available in the vicinity. To utilize this opportunity a sod cutting machine was designed, and sods of 2.25 x 5 x 0.45 m^3 were dug out, transported and placed in the large wave flume.

The cutting machine consisted of a horizontal knife, 2.25 m wide, being pulled underneath the grass at a depth of 0.45 m, followed by a steel plate of 5 m length. Simultaneously two circular steel knives cut the vertical sides of the sods (fig. 3). The steel plate bearded the sod while raising it and during the transport by truck to the large wave flume (fig. 4). For reducing the tractive forces on the horizontal knife and steel plate (and so minimizing the distortion of the grass sod) it was necessary to use some water.

The grass sods were placed in a wave flume of 200 m length, 5 m wide and 7 m depth, under a fixed slope angle of 1:8. The slope reached from the bottom of the flume (Ordnance Datum (O.D.) + 0.5 m) along 55 m up to

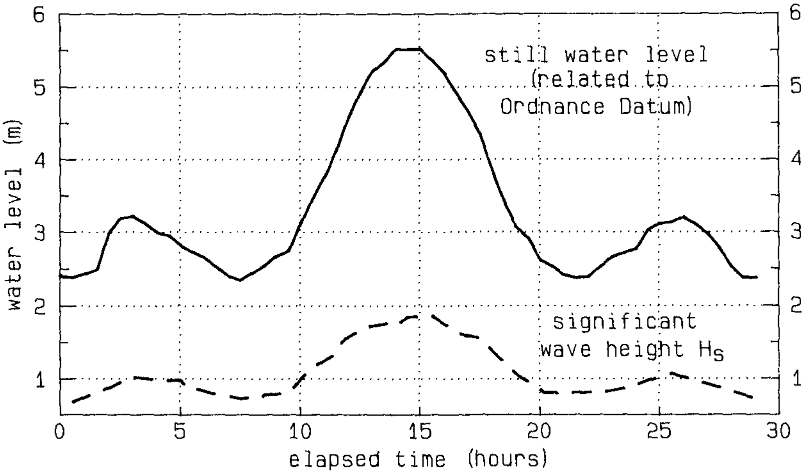

Figure 5. Realized loading conditions (water level and significant wave height) in course of time

O.D. + 7.3 m = crestheight. The grass sods were placed on a clay layer of 1 m thick, with underneath sand with D_{50} = 225 µm.

The hydraulic loading was realized by generating irregular waves with a Pierson-Moskowitz spectrum, with varying water level and wave height (fig. 5), with a peak wave period between 5.2 and 5.6 s. This stands for a plunging breaker type, falling on water cushion. The variation of the water level reproduced a storm surge superimposed on a tidal cycle, during 29 hours, reaching a maximum level of O.D.+ 5.50 m and a maximum significant wave height H_s = 1.85 m. In total the experiment lasted 48 hours, because of two stops between times for lowering the water-level, visual inspection and measuring the erosion level.

The test was executed with fresh water, while in nature the heaviest loading appears with seawater. The clay minerals in the Netherlands are mostly of the illite type (and therefore not very sensitive for dispersion). From experiences in the past with storm surges in the cold season no special effects in respect to dispersion can be derived. Therefore it is assumed that the tests with fresh water are sufficiently reliable.

The water velocities, measured at 0.05 m above the surface, were at maximum 2.2 m/s, at 4% of the waves a speed of 2.00 m/s was exceeded and the mean of the peak velocities was ± 1.00 m/s, upward as well as downward, appearing at H_s = 1.85 m. Run-up and overtopping were measured and were in good accordance with the design values.

Special care has been taken for avoiding erosion due to rim-effects on the grass sods along the walls of the test flume.

Table 1. Vegetational species (percentage)

	Test 1	Test 2 sample 1	Test 2 sample 2
Poa Pratensis (%) (Smooth-Stalked Meadow- or Kentucky Blue Grass)	65	2	2
Festuca Rubra (%) (Red Fescue)	12	20	64
Lolium Perenne (%) (Perennial Ryegrass)	6	76	29
other grasses (%)	7	0	1
other herbs(not grass),(%) among which Trifolium (Clover)	10	2	4
Total	100	100	100

2.3 Description of the grassmat

The grass was in good condition, due to 10 years of treatment, mostly by grazing sheep. The vegetation afforded initially a coverage of the soil of 50 to 80 %, which decreased to 40 to 50 % in the weeks just before the execution of the test. This was due to a lack of direct sunlight by the coverage of the roof on top of the construction hall of the wave flume, in combination with outdoor temperatures up to 25°C. Nevertheless it is not very likely that the root system has weakened significantly in this period. One week before the execution of the test the grass was cut to a length of 0.05 m. A determination of the vegetational species is presented in table 1. Some soil parameters are given in table 2.

Table 2. Soil characteristics

	Test 1	Test 2
Grass turf:		
parts < 0.002 mm (%)	18	20
parts > 0.060 mm (%)	49	46
organic material (%)	< 3	3
Supporting clay layer:		
parts < 0.002 mm (%)	35	-
parts > 0.060 mm (%)	22	-
Plastic Limit (%)	22	24
Liquid Limit (%)	36	42
Specific Weight (dried) (kN/m^3)	14.8	13.9
Sand underneath:		
D_{50} (μm)	225	-

2.4 Results

Besides the still water level and wave characteristics being measured during the experiment, the amount of surface erosion was measured during breaks of the execution, by sounding the surface of the turf with a vertical rod in a fixed pattern. Because of the standard deviation of 0.005 m in measuring a single point, the results are presented as a difference between before and after wave loading, of the mean of 30 points in an area of 5 x 5 m (fig. 6). In this way the largest erosion, of about 0.005 to 0.010 m, was measured at levels of about O.D. + 2.45 m and O.D. + 4.25 m as well. In the first mentioned area a wave height of H_s = 0.85 m (as a mean) has worked out during 18 hours approx. (fig. 5) and in the second one H_s = 1.65 m (as a mean) lasted during 6 hours. Although most of the grass leafs had vanished, the turf was in exceptional good condition without any

visual holes or cracks, caused by erosion. In general it was found that the erosion resistance originated from the upper layer of soil and roots, much more than from the grass leafs. The erosion of the clay surface occurred in a rather even way, without forming obvious cracks or holes. While eroding, a fine root structure of the grass remained on top of the clay. This root structure reduced further erosion rather effectively.
It was remarkable that at the horizontal seams between the successive sods no extra damage occurred, in spite of the presence of little differences in surface height, up to a few centimeters.

Because of the minute erosion after the storm surge simulation during 29 hours, it was decided to restart the experiment after cutting 4 holes in the grass surface. The dimensions of the holes were 0.50 m (width) x 0.20 m (length) x 0.07 m (depth). The wave height was established at H_s = 1.57 m and the water level at O.D. + 5.00 m. In the vicinity of the breaker impact the holes eroded progressively, by scouring the soil underneath the upper layer of the turf. The first visible erosion appeared after 5½ hours of loading. After 7 hours two holes were scoured out to the depth of the underlaying, very resistive, clay layer. Conclusive can be stated that the soil material of the grass sods itself was not very resistive to erosion, in contrast to the top layer with roots (of 0.03 m to, at maximum, 0.10 m) which appeared very resistive to erosion under the given loading.

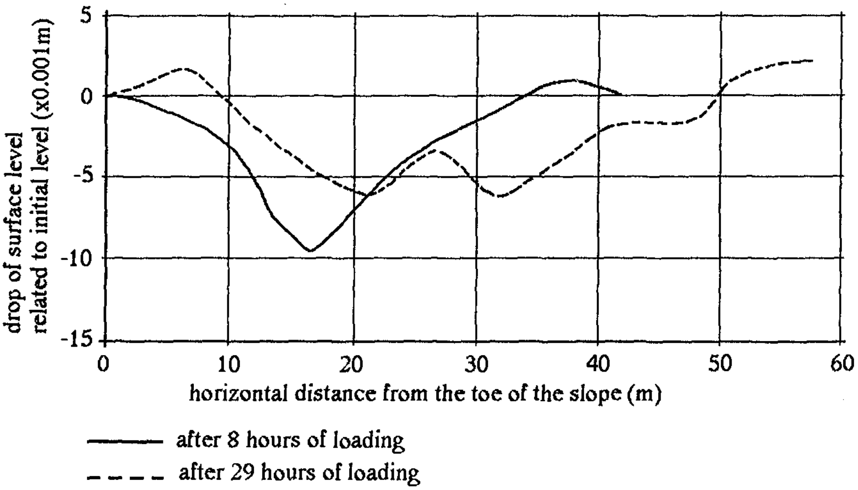

Figure 6. Averaged drop of surface, due to erosion

3. TEST 2.

3.1 The motive of Test 2.

The main objective of test 2. was the development of a quantitative and reproducible full scale test of erosion of vegetation on clayey soil under realistic hydraulic load by run-up, caused by breaking wind waves. This situation is very common on Dutch sea-dikes with a vegetational revetment on top of an armored revetment until the storm surge design water level. In that case the waves brake on the rigid revetment while the grass is only loaded by run-up and run-down.
Therefore 4 problems had to be solved:

1. Cutting and transporting large scale grass sods to a testing location.
2. Generating realistic and reproducible hydraulic loads.
3. To control rim effects and other shortcomings that distorted former experiments in laboratory conditions.
4. Defining a measurable erosion rate parameter.

Only if the conditions mentioned could be satisfied, it would be meaningful to establish an erosion/loading rate on a given grass/soil sample of a well defined condition. Two samples have been taken and tested, under the same conditions, to determine the reproducibility of the test. The two samples originated from the same sea-dike slope in the north of the Netherlands.

Figure 7. Two grass sods for Test 2. being dug out

3.2 Experimental set-up

In Test 2, a grass sod of 0.5 m thick, 1 m wide and 10 m length was dug out as a whole from a sea-dike as follows. An I-girder of 10 m long and 1 m high with one flange cut off was placed with its web horizontally, in a groove, dug out next to the sod to be taken out. The sharp edge of the web was pressed horizontally by hydraulic pistons at 0.5 m below the grass surface underneath the sod. Then the other side of the 1 m wide sod was dug free and the I-girder functioned as a bearer during the take up, the transport as well as during the whole test (fig. 7).
After transport it was put in a test flume with slope angle 1:4. Before starting the experiment, the flange first taken off, and elongating steel plates forming the sides of the flume, were welded on the I-girder. So the test was carried out on an almost undisturbed sample within the steel flume of 1 m wide.
Special care was given to the filling of the slot between the soil and the vertical wall of the steel flume. It was filled by a clay-bentonite mixture and covered by course stone-chipping and a strip of Enkamat, a non woven fabric of course filaments. This fabric protects the underlaying vulnerable rim, with a roughness according to that of grass, without introducing renewed rim-effects on the transition to the plain grass.

The steel flume described before was placed in a larger (2 m wide) concrete flume next to a weir in the river Meuse. Over this weir a falling water head of about 5 m was available for generating the demanded hydraulic loading. Wave run-up and run-down were generated by simulating a breaking wave. Wave breaking was simulated

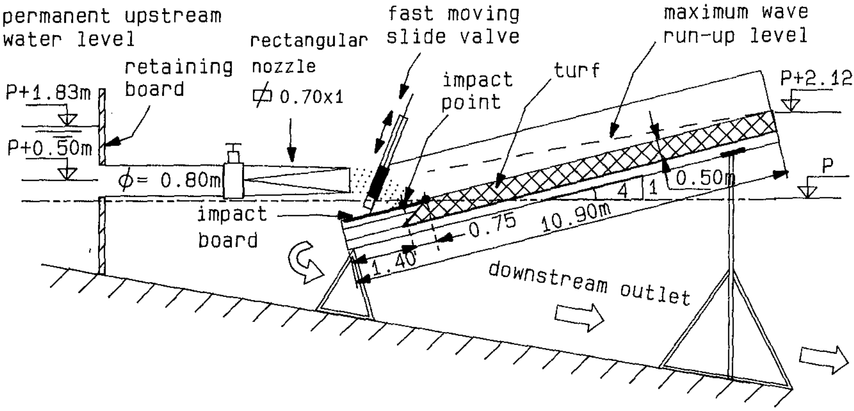

Figure 8. Experimental set-up of TEST 2 with simulation of wave run-up

by periodically (once in 7 seconds) intermitting a water jet of 2.2 m^3/s, streaming out of a rectangular nozzle (0.7 m high, 1 m wide) at the end of a horizontal pipe (fig. 8).
Designing the set-up for the hydraulic loading, a small scale model was built for testing the lay-out. After building in full scale and placing the grass sod in situ the hydraulic loading was calibrated on a temporary (for some hours only) wooden board, placed 0.10 m above the grass to be tested. For simulating the roughness of grass the board was roughened by placing (and glueing) small wooden cubes of 0.03 x 0.03 x 0.03 m^3 in a diamond-shaped pattern with edges of 0.9 m. In this way 3 usable hydraulic conditions were tuned in, each of heavier hydraulic load.
Starting the experiment with sample 1, at first the two lightest conditions were used, each during one hour. After coming out that only the heaviest possible loading should give a significant erosion within reasonable time, only the latter was used.

Free falling (3 s approx.) the water plunged on a roughened wooden board, 0.75 m before the downward rim of the turf, so creating an upward streaming parallel to the grass surface. Before starting the next "wave" the time remaining was enough for all the water running down. The maximum up and down velocities parallel to the grass surface came to 4.0 m/s, and the maximum thickness of the water layer was at maximum 0.70 m at the downward rim of the turf, decreasing uniformly along the grass surface up to the point of maximum run-up, 8 m upward along the slope. This equals, according to the theory of Battjes and Roos (1975), a wave with height $H = 3.6$ m and period $T = 6.8$ s.

3.3 Description of the grassmat

The grass was in good shape before starting the tests. The soil coverage by the vegetation was 70-85 % for sample 1 and 70-95% for sample 2. A determination of the vegetational species is presented in table 1.
In the winter before the test the root content as a function of depth was determined at the dike location the grass was taken from. Two samples were taken. The total weight of roots over 0.50 m depth was 29 g/dm^2 (sample 1) and 35 g/dm^2 (sample 2), of which 10 and 18 g/dm^2 (35 and 51 %) in the upper 0.05 m, and 94 and 95 % in the upper 0.40 m.
The most significant difference between the two large sods was the somewhat better condition of the second one at starting the test, and some difference in the dominating grass species in the turf (see table 1).
Some soil parameters of the turf are given in table 2. It

is noticeable that the soil of the samples was not homogeneous, but there were several patches of sand present.

3.4 Results

The amount of erosion was gauged by vertical rods touching the surface in a fixed pattern, during breaks of the simulated wave loading. The erosion at the point of maximum damage at the end of the test of each sample is given in fig. 9. During the first 3 hours of loading hardly any erosion was visible. In the next period from 3 to 10 hours, in the lower 5 m along the slope the gras leafs eroded away. In general it was established that the upper 0.03 m of the turf eroded in a rather even way, without obvious cracks or holes. Thereafter, (between 10 to 15 hours with sample 1, 15 to 25 hours with sample 2) cracks developed.
In sample 1 after 16 hours the rate of erosion increased. After 18 hours, when at 0.6 m from the lower rim the erosion is 0.08 m deep and 0.60 m long, lumps of soil started breaking away and after 22 hours the bottom of the turf was reached.
In sample 2 the increase of the erosion rate appeared after 25 hours at 2.5 m from the lower rim of the turf. After 40 hours the hole was 0.20 m deep and 0.40 m long and the bottom was reached after 41 hours.

As said sample 2 hold out longer than sample 1. Partly this may have been caused by a somewhat better condition of the grassmat as a whole, but it is important to

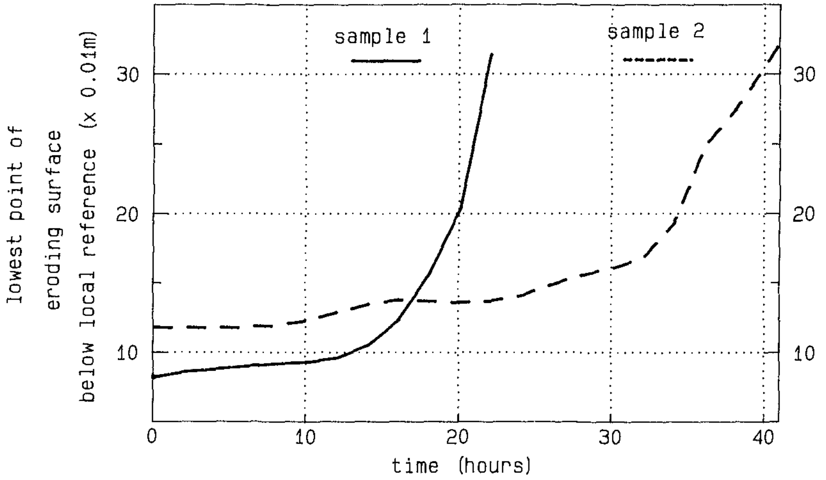

Figure 9. Maximum erosion depth in course of time

mention that sample 1 had a bold patch in the heaviest loaded zone, caused by lack of sunlight during the two months before test by a wall sustaining wooden lath at 0.20 m above the grass. Although 20 hours for sample 1 is significantly shorter than the 40 hours lifetime of sample 2, the top layer caused mainly the total resistivity, even at the bold patch. This confirms the lesser importance of the grass leafs, and shows that the resistivity of the upper root layer can sustain a period of weak growth of the grass, which is likely to be important for the condition of the sea-dike grass in the winter and early spring.

During the process of erosion it was clear that small unevenness of the soil nor small holes such as wormhole were harmful at all. The thick tap-roots such as from the Taraxacum Officinale (Dandelion) caused some extra erosion, but not in such a way that the damage that occurred was influenced significantly.

Beyond the detrition of the grass leafs, in general two types of erosion could be distinguished:

1. Areas were the clay remained rather bare behind (up to an erosion of 2 to 3 cm) and
2. Areas were a fine network of roots stayed behind after the soil washed out. This network retards further erosion.

In the first mentioned areas the Lolium Perenne (Perennial Ryegrass) dominated, while in the second case Festuca Rubra (Red Fescue) dominated. From botanical descriptions it is well known that the Festuca Rubra has a wider and finer root system than the Lolium Perenne.

From the areas were the grass top layer was eroded 1 to 3 cm, without final distortion, is was hardly possible to grow up the grass in the laboratory from the remaining roots. This means that the grass, after withstanding such a heavy attack, will need one or more growing-seasons for recovery.

Parallel to the full scale test described, laboratory tests were carried out on small cores (ϕ = 66 mm) taken from the dike location in the winter, from the upper 0.05 m as well as from a depth of about 0.40 m. These erosion test by a rotational water apparatus confirmed qualitatively the large difference between the erosive resistance of the turf at the two depths.

4. CONCLUSIONS

4.1 In two different ways the digging out of grass sods of about 0.50 m thick and an area of 10 to 12 m2, transporting and placing them as a whole was possible.

4.2 Successful simulation was possible of wave attack by direct impact of breaking irregular waves up to Hs = 1.85 m and by wave run-up and run-down equivalent to regular waves of about H = 3.6 m.

4.3 The measures to overcome the influences of rim-effects along the grass sods on the test results were successful.

4.4 A general insight and a quantitative description were obtained of the erosion process of the tested grass from real sea-dikes under rather realistic boundary conditions.

4.5 It was affirmed that a proper quality grass on sea-dikes can have a high resistance against erosion by storm surges. Thus was decided to enlarge the sea-dike described in paragraph 2.1 as designed, without reinforcement of the grass revetment.

4.6 In the two cases with soil of rather sandy clay, the resistance was concentrated in the top layer of 0.03 up to (at maximum) 0.10 m, composed of soil and roots.

4.7 The type of erosion depends on the type of grass, particularly the root structure. A wide and fine root-structure (such as Festuca Rubra) leaves a fine root-structure behind while eroding, which retards further erosion. Other grasses, such as Lolium Perenne, omit this property, which causes a lower erosion resistance.

4.8 In two specific cases a quantitative erosion resistance is determined.

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