THE USE OF VETIVERS IN COASTAL ENGINEERING

by

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ABSTRACT

Vetiver grass is a sustainable and innovative solution for the protection of banks. It is shown that Vetiver grass is able to establish a full-stop of bank erosion caused by rapid drawdown. Therefore it provides us with strong indications that it is highly suitable as an anti-erosion measure. A combination of cohesive soil and Vetiver grass provides the best protection against erosion, which implies that it is highly suitable for banks in delta areas, which consist pre-dominantly of cohesive soil.

A single hedge of Vetiver grass planted on the outer slope of a dike can reduce the wave run-up volume by 55%, in contrary with sod-forming grasses that give no reduction. Planting multiple hedges along the contour of the outer slope might result in even more reduction. The application of Vetiver grass on existing dikes may provide a substantial reinforcement of these dikes.

The advantages of Vetiver grass above conventional methods with the use of stone are numerous:

- Vetiver grass is sustainable. Vetiver hedges of over 100 years old have been found. Vetiver grass is not invasive and no significant diseases are known. Vetiver grass will, in contrary with traditional methods, increase in strength in time.
- Vetiver grass is an economic attractive solution. In most countries in South-East Asia Vetiver grass can be planted for less than $ 3 per meter, while solutions consisting of stone and concrete are expensive in delta areas.

Vetiver grass allows people to protect their own property. Since the costs are low and it is easy to use local initiatives can be easily achieved.

1. INTRODUCTION

Traditionally banks are protected against wave action with stone or wood revetments,. However, these are quite costly constructions. Also in low lying areas, the land is protected by dikes, often with a significant freeboard, because of the anticipated wave overtopping. Recent research has shown that Vetiver grass (*Vetiveria zizanioides*) can be used as a cheap method to protect shorelines and to reduce overtopping. In several countries field test are done, and also some guidelines are given (eg. in Vietnam [Truong and Pinners, 2007]). However, there is some lack in the fundamental understanding of the behaviour of Vetiver grass in coastal engineering. For this reason Delft University of Technology has set up a research program to gain more understanding.

Since half of the world's population of 6.5 billion people lives in densely populated delta areas, space is limited. Bank erosion and inundation of land therefore cause major economic damage and loss of human lives. Hence good protection of the banks of delta areas is important.

There are several causes for bank failure in deltas other than overflow where the water level exceeds the bank level. The channels and rivers in deltas are often used as waterways. The banks of these waterways suffer from vessel induced loads. Bank protection is designed to cope with these loads and stop the erosion of the banks. Since the flow velocities in deltas are generally speaking low, the erosion caused by flow is limited. Shores adjacent to the sea or large estuaries are exposed to wind waves. These shores often exist of dunes and dikes that protect the hinterland. These dikes and dunes should not only be able to cope with the water level but also with the wave induced loads. Waves can erode the outer slope of a dike and when the crest level is too low waves, overtopping the dike, can also erode the inner slope causing failure of the dike and due to this inundation of the land.

Vessel induced loads and wind waves are important causes for bank failure. Bank protections in deltas are often designed to cope with these loads. The protection can consist of wood, rock or

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concrete, sometimes in combination with an earth body in case of a dike. The earth bodies and the stony materials used, are often expensive since space, stones and wood can be scarce in deltas.

The use of vegetation as bank protection can be a less expensive measure. Mangroves, reeds and grass sods are already applied as bank protection in many deltas in the world. In addition to these species other vegetation can be used as well. A prime candidate for use as bank protection is Vetiver grass.

Vetiver grass (*Vetiveria zizanioides*) is a clump-forming perennial grass, which presumably originates from the Asian continent and thrives best in tropical conditions. There are twelve known varieties of Vetiver grass; the most relevant one being the south Indian genotype of *Vetiveria zizanioides (L) Nash* for it does very rarely form seeds and therefore has a very low weed potential.

Anatomically Vetiver grass can be classified as a hydrophyte (an aquatic plant) because its roots possess aerenchyma-tissues[5] with air passages that enable flooded roots to snorkel air from above-water plant parts. This is why Vetiver grass is able to survive several months of submergence [Xia *et al* 2003, Ke *et al* 2003]. However, it is also known to thrive under xerophytic[6] conditions.

Vetiver grass is known to form a dense and deep root network and is able to achieve a high growth rate, is tolerant to a large variety of soil conditions. Vetiver grass cannot cope with severe frost, so its use is limited in tropical and sub-tropical areas. Maaskant (2005) showed that Vetiver grass can grow in an brakish environment (salt concentration 9 ‰). It also has a high root tensile strength. The stems of the grass are very thick and dense compared to other grass species as can be seen from the table below:

Grass	M (m-2)	d (mm)	I (mm4)	E (Gpa)	MEI (N)
Switchgrass old	3700	3.15	4.8	8.5	152
Switchgrass young	7400	3.85	10.8	2.9	231
Vetiver	3500	9.10	337	2.6	3060
Miscanthus	10400	2.25	1.3	3.5	46
Fescue	6870	1.75	0.2	0.2	1

Table 1: Stem density, stem diameter, moment of inertia, modulus of elasticity, MEI product (Dunn et al., 1996)

These distinct properties among others make Vetiver grass highly suitable for application as a bioengineering species. It is therefore used for all kinds of purposes all over the world for decennia now, for example as a measure against top soil erosion of agricultural land and mountain- and hillsides.

More recently, it has also been tested as a bank protection on several test sites (in China, Vietnam, Australia and the Philippines). These tests showed promising results for the use of Vetiver grass as a bank protection [e.g. Ke *et al* 2003, Le Viet Dung *et al* 2003] but give no insight in the processes involved and their quantitative effects.

However, when applying Vetiver grass as a bank protection, it is necessary to have a higher level of qualitative and quantitative knowledge on the effects of Vetiver grass on the main causes of bank erosion, for this may reduce risks as well as costs drastically. Also the growth characteristics of Vetiver grass on the banks have to be reviewed, since no qualitative values are known. As mentioned above, in a delta area vessel-induced loads and wind waves are dominant eroding agents. Therefore the following subjects have been studied:

- Influence of soil type and phreatic level on Vetiver grass
- Vetiver grass as bank protection against vessel-induced loads
- The use of Vetiver grass as an armour layer on a dike under wave attack

[5] These type of cells enable gas exchange
[6] Areas with very little free moisture

To study these subjects, tests have been performed at the Laboratory for Fluid Mechanics and the Botanical Garden both of Delft University of Technology.

2. INFLUENCE OF THE SOIL TYPE AND PHREATIC LEVEL ON VETIVER GRASS

Besides the investigation of the effects of Vetiver grass on erosion, it is also important to retrieve data on if and how Vetiver grass thrives on banks. For application of Vetiver grass the influence of phreatic level and soil type on its growth rate are for a large part still unknown but both may be very important, especially in the planting phase. The experiments with respect to this subject are discussed first, after which the experiments with respect to erosion are considered.

Experiment

Vetiver plants (obtained by splitting full-grown Vetiver plants and, as far as possible, washing out the material between the roots) were planted into three pots filled with non-cohesive soil (MX) and three pots with cohesive soil (C). The stems of the Vetiver grass were cut off at a length of around 30 cm, while the roots were cut off at a length of 20 cm, both measured from the surface level. The pots were put into PVC pipes that were watertight with a PVC plate at the bottom as shown in figure 1.

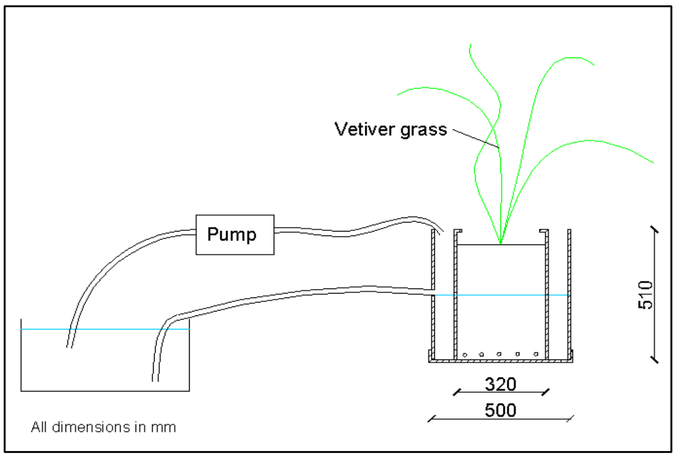

Figure 1: Sketch of the test setup (medium groundwater level)

The PVC pipes were filled with water up to three different levels, differing approx. 17 cm from each other. Both soil types thus had pots with three groundwater levels situated 1, 18 cm and 35 cm below surface level, respectively referred to as high, medium and low. The water level in the PVC pipe corresponded with the groundwater level in the pot through holes in the pot and was kept constant. The test setup was situated in a green house to provide a good (tropical) growing climate. This means that the temperature was kept approximately at 20-25℃ (with the use of heating lamps) and that the atmospheric humidity was also kept high. Each stem of Vetiver grass has several leaves and each leaf was measured individually from the cut to the top, 2 times a week for a period of 54 days.

Results

All results are based upon the observations with respect to length increase of the leaves in time.

With respect to the groundwater level differences of the non-cohesive soil type (MX) the following results were obtained: Vetiver grass with a low groundwater level did have a higher rate of growth than the plants with a medium (10%) and with a high groundwater level (30%). The plant with the high groundwater level did have the lowest rate of growth considering length increase, namely 20% lower than medium groundwater level.

When considering the groundwater level differences of the cohesive soil type (C) the following results were obtained: The plant with the high groundwater level did have a lower mean rate of growth than the medium groundwater level (17%). However, the plant with a low groundwater level showed deviation from the expected higher growth rate. It showed a sudden increase in growth rate around 42 days, which was probably caused by a lower level of light intensity, while the other pots did have full light availability. However, the cause of this light interception (another Vetiver grass plant) was removed after 42 days after which the light intensity became equal again for all three pots. The high level of sensitivity of local circumstances on the growth rate of the plants is clearly to be seen in figure 2.

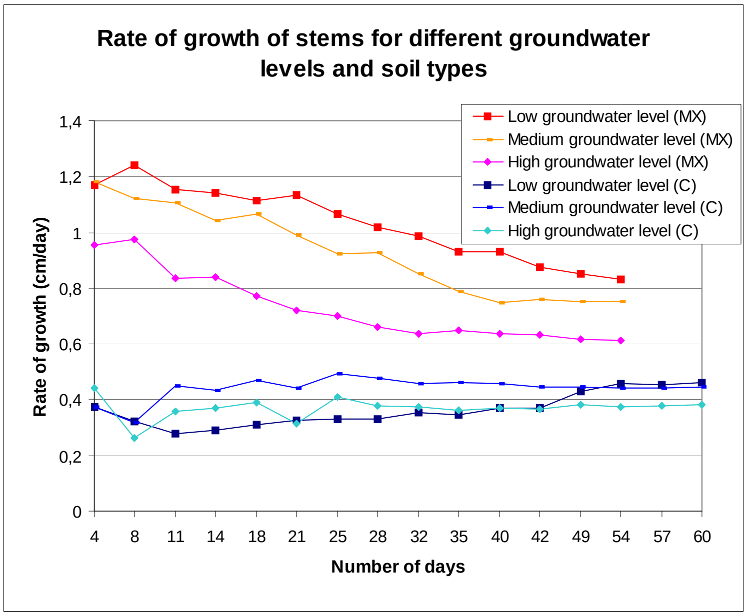

Figure 2: Results experiment

All comparisons were executed with the results after 54 days. The results of the pot with the low groundwater level were not included in the comparison because of the above mentioned inaccuracy.

A possible explanation of the decrease in growth rate at a higher groundwater level may be the lower level of available oxygen for the roots. Another possible explanation may be that the roots grow towards the groundwater level as quickly as possible, in search of water. Therefore the presence of water in the starting phase (high groundwater level) will then result in a lower growth rate.

The growth rates of the plants with the cohesive soil were approx. 40-50% lower than the growth rates of the plants with the non-cohesive soil. This trend is in correspondence with theory, for e.g. Kirby and Bengough (2002) mentioned the slowing down of the rate of elongation of roots caused by strong soil.

The results of all growth rates were tested on significance level. The results of these tests are presented in figure 3.

3. GRASS AS BANK PROTECTION AGAIN VESSEL-INDUCED LOADS

Vessel-related erosion, erosion of unprotected banks and the protection of banks by vegetation are all still poorly understood phenomena at the current state-of-the-art. Therefore, more insight in the relevant physical processes is necessary. A theoretical investigation of all possible influences of Vetiver grass on bank erosion, including erosion caused by ship traffic was carried out by Jaspers Focks (2006). In total 14 possible adverse and/or beneficial effects were found. This investigation resulted in hypotheses related to the mechanisms with which Vetiver grass should be able to prevent erosion, and therefore had to be investigated into more detail by experiments. The results provide implications for the suitability of the usage of Vetiver grass as a bank protection.

River banks are pre-dominantly cohesive [Mosselman 1989]. Erosion of these river banks can be divided into two distinct processes: entrainment of particles or mass failure under the influence of gravity [e.g. Mosselman 1989, Duan 2005]. A third process, subaerial preparation [e.g. Abernethy and Rutherfurd 1998] is not mentioned by all authors, for it has no direct relation with river-processes. In contrary with fluvial entrainment of non-cohesive material, the mechanics of fluvial erosion of cohesive sediments is poorly understood [Millar and Quick 1998]. Cohesive soils are normally speaking more resistant to particle entrainment than non-cohesive soils [ASCE 1998]. CUR (1993) after Riemsdijk and Van Eldik (1992) mentioned that the loads caused by currents (tested at 1.1 m/s) are too weak to significantly erode cohesive soils.

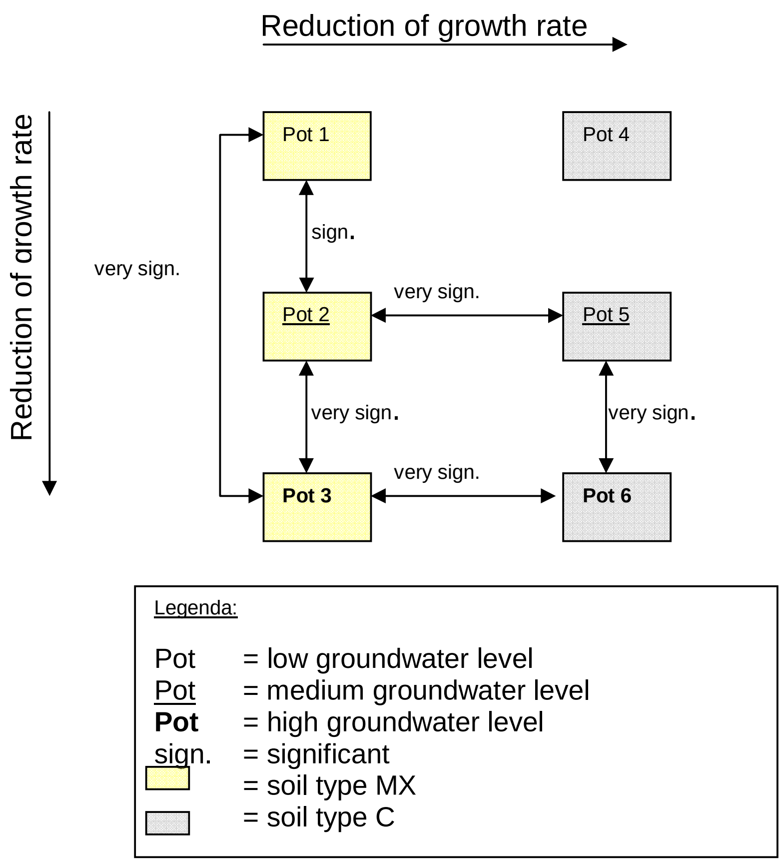

Figure 3: Overview results

When considering the erosion of cohesive banks by vessel-induced loads, it is therefore assumed that mass failure is the dominant eroding mechanism. The limiting riverbank stability usually occurs when bank strength is reduced by increased unit weight of the soil and the excess pore-water pressures during a drawdown [Darby and Thorne 1996]. A rapid drawdown at the bank is caused by either the waterlevel depression caused by a ship or by the water movement just before a secondary wave breaks on the slope. Experiments with respect to erosion were focused on mass failure caused by rapid drawdown. In this study mass failure was divided into small scale and large scale mass failure. Large scale refers to deep-seated failure planes, while small scale refers to shallow-seated failure planes and the so-called "pushing off" of material. The direct influence of Vetiver grass on relevant soil parameters (undrained shear strength and saturated specific weight) related to large scale mass stability was investigated by execution of laboratory tests. An increase in the factor of safety (as used in limit equilibrium methods) of approximately 20% by the presence of Vetiver grass was found [Jaspers Focks 2006], mainly by an increase in undrained shear strength. These results, however, showed a large spread and were not significant. Therefore these experiments are not discussed into more detail. The focal point is at the experiments with regard to small scale mass failure.

Experiment

The influence of Vetiver grass on small scale mass failure was tested using a physical model test. The drawdown caused by passing ships was reproduced with the use of a wave flume. Several series of successive drawdowns were carried out on a representation of a bank. The variables in these tests were the soil type, namely a cohesive (C) or a non-cohesive (MX) soil, and the presence or absence of Vetiver grass. A sketch of the test setup is shown in figure 4. The position of the hydraulic wave flap was adjustable into detail in x-direction and in time

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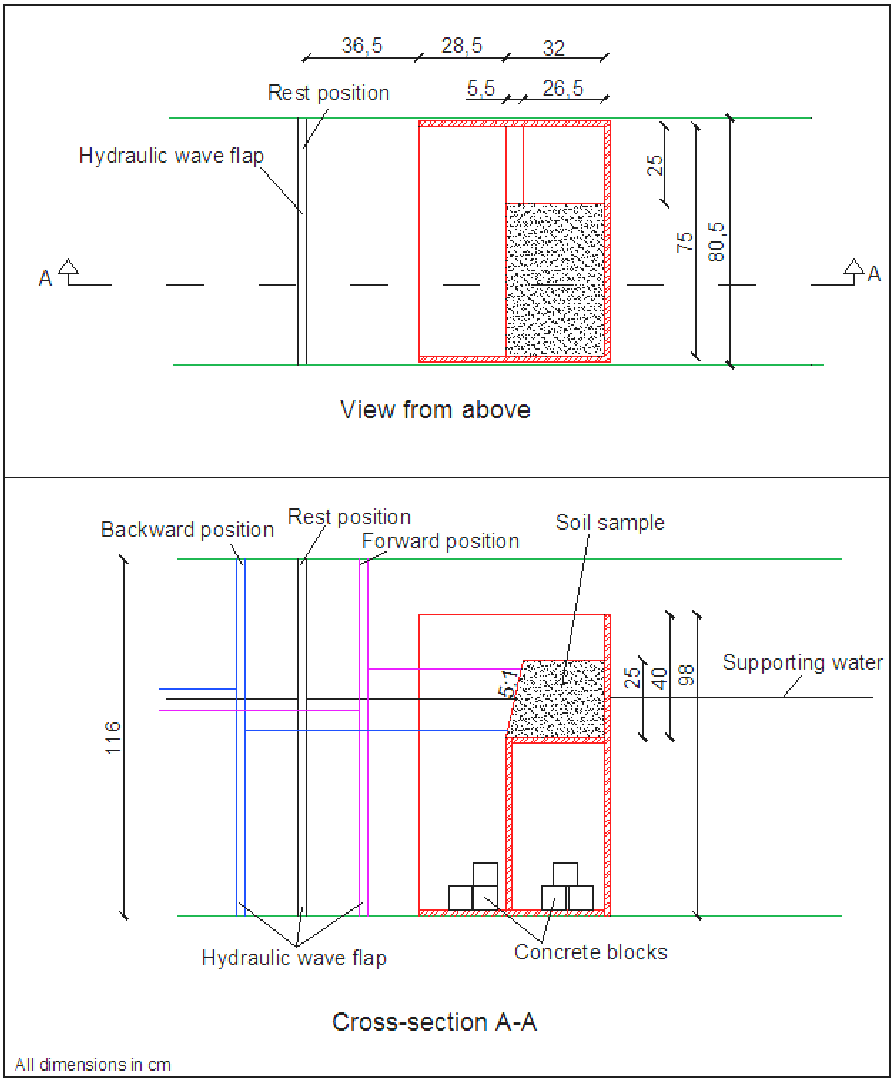

Figure 4: Lay out of the bank erosion experiment

The Vetiver grass with soil type MX was planted three months beforehand and the Vetiver grass in soil type C was planted two months beforehand. The soil samples were placed on the wooden construction. When testing soil with Vetiver grass, two Vetiver grass samples were tested at the same time. After placement of the samples the surface water level was raised up to half of the height of the soil sample. The initial topography of the slope was determined at equidistant intervals of 0,05 m parallel (horizontal y-direction) and vertically (z-direction) in reference to the slope, with a horizontal measuring needle (precision 0,001 m) in the horizontal direction incident on the slope (x-direction). A wave height meter (precision 0,0005 m) was used to obtain the number of simulated ship passages and the water level changes. The groundwater level at 0,25 m behind the slope was measured before the start of the test to check whether or not the groundwater level corresponded with the water level in front of the slope. These measurements were performed with a measuring rod (precision 0,001 m) in a borehole (ø 0,02 m). The test was started at the moment the groundwater level and the surface water level were equal. During the test with soil type C the groundwater level was measured regularly (after each 100 cycles) to check if it remained constant. At several moments during the experiment, after a certain number of cycles the experiment was paused. The hydraulic wave generator was brought back into its resting position and the topography of the soil was measured, after which the experiment continued.

Results

The erosion of the cohesive soil was observed to be dominantly caused by small scale mass failure. The amount of eroded material of the cohesive soil was approximately 8-10 times smaller using Vetiver grass, which is also to be seen in figure 5. These numbers are solely meant as indicative numbers.

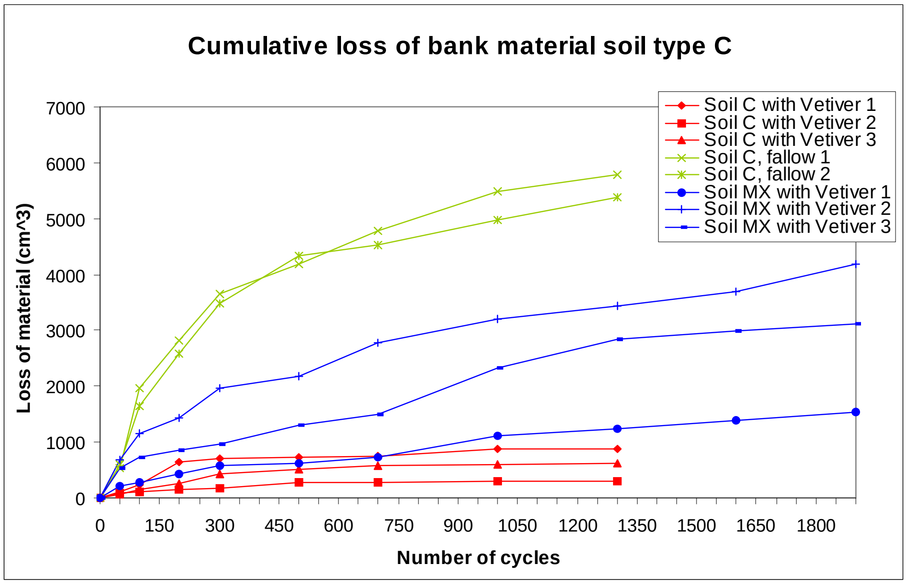

Figure 5: Experiment results

The erosion of the non-cohesive soil was observed to be not specifically related with small scale mass failure, but was reduced also drastically. The fallow non-cohesive soil was unstable beforehand and showed an extremely high erosion rate. Due to this no quantitative comparisons could be made.

It was found that a combination of cohesive soil and Vetiver grass did have the lowest amount of erosion, even a full stop of erosion was recorded after approximately 800-1000 cycles.

4. VETIVER GRASS AS RUN-UP REDUCTOR

Vetiver grass can be planted on the outer slope of a dike to reduce the wave run-up. The roots of Vetiver grass will retain the soil on the outer slope and the stiff stems will reduce the amount of water overtopping the dike. Vetiver is able to grow in brakish environments [Maaskant, 2005]. The outer slopes of sea dikes , especially the higher parts, do occasionally get splashes of salt water, because of wave run-up. However, the environment can be considered a fresh water environment because of the fact that Vetiver is mainly under the influence of rainwater when placed above the still water level during storms.

Vetiver grass cannot form a sod as low grasses can. Vetiver grass therefore should be planted in rows along the contour with low sod forming grass in between. The combination of sod forming grass and Vetiver grass hedges reduces the construction costs and material use of a dike. Vetiver grass planted on the outer slope can reduce the run-up in two ways:

- Reduction of the run-up height
- Reduction of the volume of water passing the level where Vetiver grass is planted

Research has been done on the reduction of run-up by rough slopes [Van der Meer, 2002, Klein Breteler et al. 1996]. However, no research could be found on the effect of objects protruding the run-up flow other than crown walls on top of a breakwater. Because scaling down Vetiver in physical experiments is not possible, the experiment is split into two parts. Part 1 focusses on the run-up reduction du to resistance onsisting of vertical elements (run-up as function of the percentage of opening) and part 2 focusses on the determination on the percentage of opening in real Vetiver grass.

Experiments, part 1

To determine the effect of one hedge of Vetiver grass, small scale tests have been performed in a wave flume of 0.8 m. wide. In the tests the run-up height and the run-up volume is measured for situations with and without a hedge. The dimensions of the elements of the tests are shown in figure 6

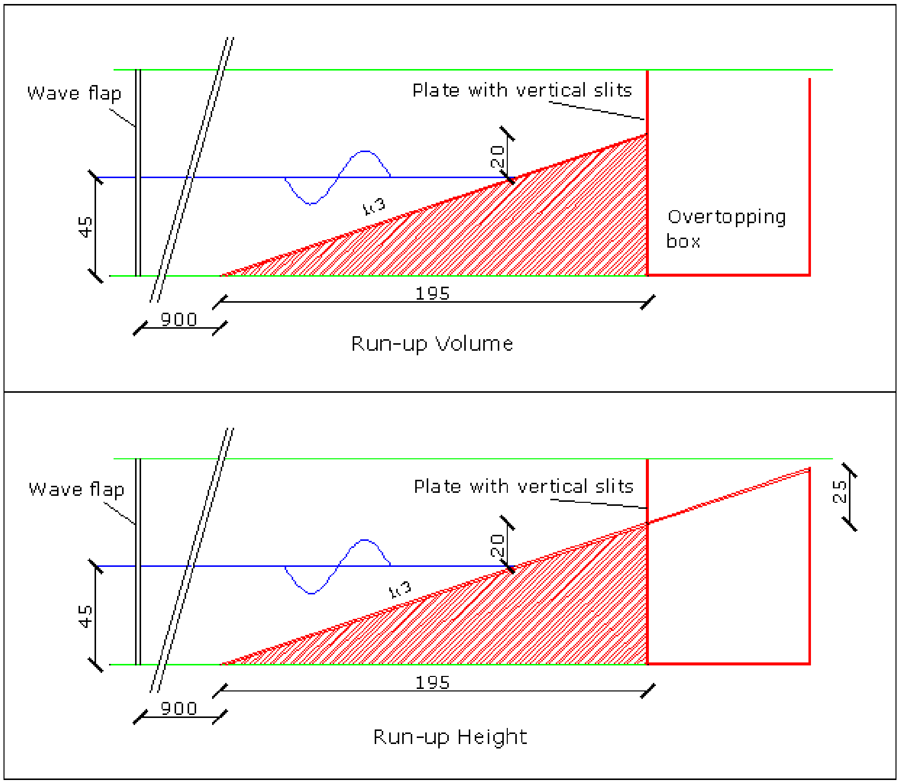

Figure 6: Experimental Set-up

As metnioned above, it is not possible to scale Vetiver grass for the run-up tests, because of scale effects related to the viscosity of water and the complex interactions of the stems in real Vetiver grass. [Algera, 2006]. Therefore the backwater-discharge relationship has been used to model Vetiver grass. Vetiver grass hedges have been tested for stationary flow situations in flumes [e.g. Dalton et al, 1996, Metcalfe et al, 2003, Dabney, 1996, Meyer 1995]. From these tests a backwater-discharge relationship can be found. In figure 7 the relationship found by Dalton et al, 1996 is shown together with the theoretical backwater discharge relationship of a plate with vertical slits with a blocking of 75 %.

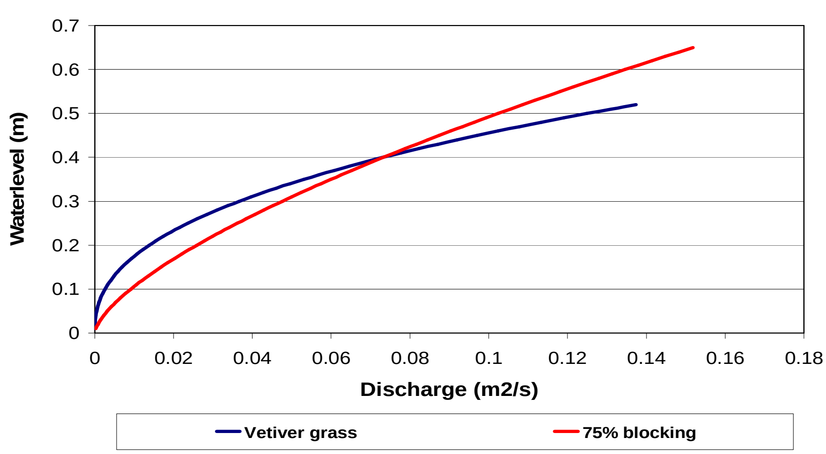

Figure 7: Backwater-Discharge relationship Vetiver grass

For stationary flow situations a plate with a blocking factor of 75% can be compared to a Vetiver grass hedge. Different plates with a width of 8 mm. with different sizes of the openings have been tested, as can be seen in table 2. With the oscillatory flow through the gaps, flow through the slits might become laminar and the width of the slits might influence the results. Therefore different plates were tested to see whether laminar flow would occur.

Blocking	Number of slits	Width of slits	Spacing
0%	1	80 cm	-
75%	8	2.5 cm	10 cm
75%	4	5 cm	20 cm

Table 2: Different plates used for testing

Wave climates used for the tests are all regular waves and range from 0.12 to 0.16 m. The wave generator used was equiped with automatic reflection compensation. The run-up level is measured with a point gauge (precision 0.001 m). The average of several waves is used to determine the run-up height. After the run-up level is determined the slope above the hedge is removed and the water passing the hedge is collected in a box. After a controlled number of waves is passed, the box is closed and the volume of water is measured with a weighing device (precision 1.0 kg). The measurements are compensated for water level decline because of collecting water in the box. Secondary effects caused by the partial reflection of the tongue against the plates is considered negligible. The overestimation because of the fact that no water is running down the slope, when the water is collected in a box, is taken into account. A detailed description of the tests can be found in Algera, 2006.

Results

The results of the run-up tests are presented below. The reduction of the run-up height and the volume are set out versus the run-up height of the smooth slope (R_u) minus the vertical distance of the plate to the undisturbed water level (z).

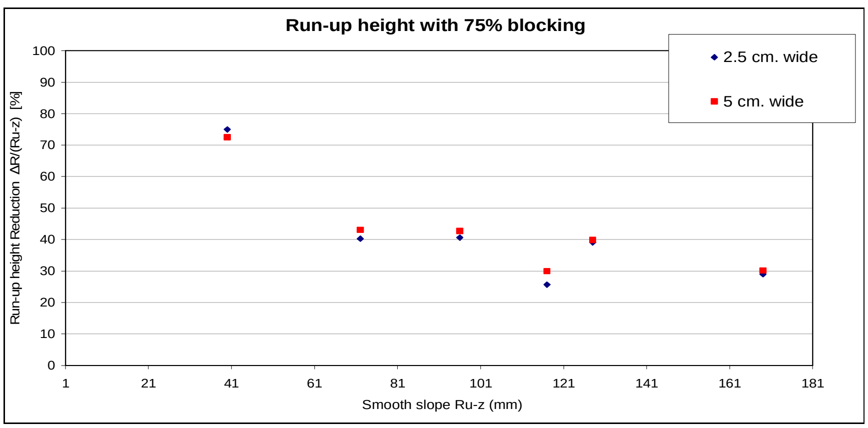

Figure 8: Reduction of the Run-up height

The results for both the plates with the different opening size are quite similar. From the test results it can be seen that no clear trend can be observed from the graph showing the reduction of the run-up height. Further tests have shown that the reduction of the run-up height mainly depends on the surf similarity parameter [Algera, 2006].

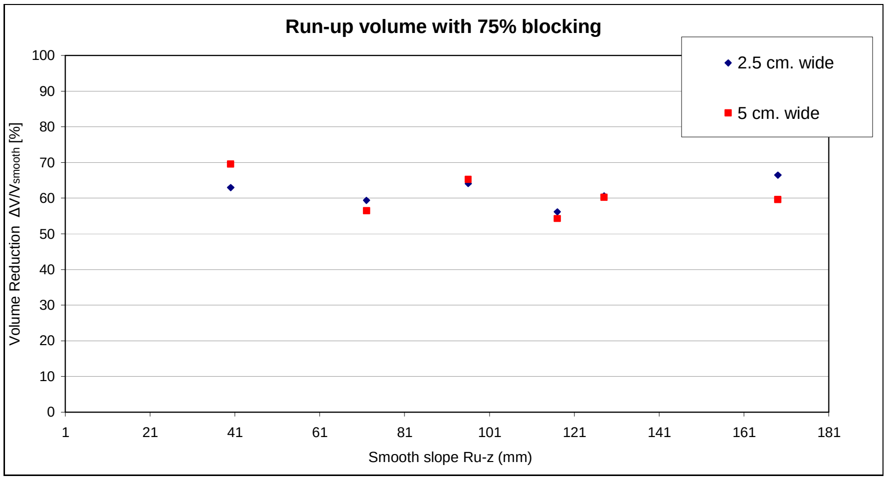

Figure 9: Reduction of the Run-up Volume

The similarity of the reduction in volume indicates that the flow through the openings during the run-up tests is mainly quasi-stationary. The plates, that resemble the Vetiver grass hedge in stationary flow, also resemble Vetiver grass well in run-up situations. The reduction of the run-up volume is above 55 % and is constant for the different run-up heights tested. This is in good accordance with the theory from [Algera, 2006]. Also for higher run-up heights than the heights tested the reduction of the run-up volume remains constant [Algera, 2006]. Tests with plates with a blocking factor of 60% gave a reduction of 40% of the run-up volume.

Experiments with real grass

In order to investigate the real resistance ofVetiver a set of experiment were performed in in a 15m long and 0.4m wide rectangular glass-walled flume with the depth of 0.4m [Vu, 2007].

full scale test to simulate run-up through Vetiver

- The slope is constructed as a simple berm slope using plywood, with the slope angle of 1:30 and the total length of 6m.
- A hedge of Vetiver grass is planted at the upper end of the slope with the length of 0.5m.
- The reservoir is constructed using wood on one side of the flume. Water will be supplied into the reservoir by the water system which is available in the laboratory. The reservoir is used for wave making by opening the vertical hinge gate.
- An opening mechanism is setup to control the opening of gate which is made from thickness wood and steal.

Vetiver grass used in this research was collected from Botanical garden, Delft University of Technology. It was planted in a greenhouse under the temperature of ap-proximate 20 degrees Celcius, and the humidity of 85%. The Vetiver grass which used during the tests had 6 months aged and the average height was 1.5m. Each mature cluster of Vetiver grass includes 12-15 culms with the average diameter of 3cm. The leaves of the Vetiver were cut at about 50cm on the top and the root length was only 20cm.

The Vetiver grass is planted in a process as follows:

- Firstly, the Vetiver grass was planted in a container which has the same size as the required size in the test Length- Depth- Width: 0.5-0.2-0.4m, at least 3 weeks before the test with the highest density is 530 stem per m2.

- Secondly, the Vetiver grass was collected after 3 weeks growing in the container in order to be sure that its root already combined. Then they were put into the position in the flume.

Different pressure transducers are used to record water depth and to measure flow velocity along the flume, especially in the area around the Vetiver grass. To record the data, a PC is connected to the transducers. The water layer thickness is measured along the flume by using a wave Gauge Height Meter (GHM).

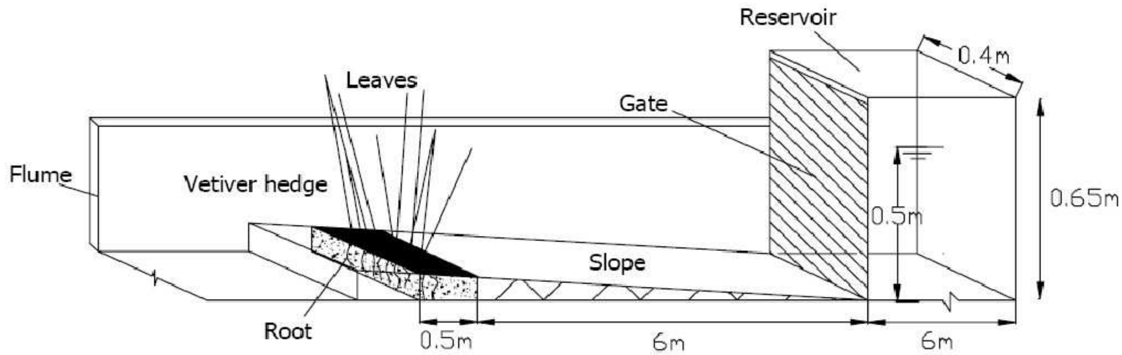

Figure 10: Set-up of the experiment with real Vetiver grass

The waves were simulated by bores (similar to dam breakage). The total volume of water of each individual wave was controlled by the amount of water in the reservoir. It means that the flow through the Vetiver hedge could be considered as continuous flow in a short time. Changing the waterlevel inside reservoir could produce different waves. Figures 11 and 12 illustrate the reduction of discharge overtopping and the water level inside the reservoir.

The results of the overtopping discharge corresponding with different density of grass are presented below. This overtopping discharge reduction from the density of zero to 563 stems per square meter rises significantly from a value of just fewer than 5% up to a value of nearly 65%. That trend still increase with the increasing of density which is larger than 530 stem per square meter. The water level in front of the Vetiver hedge can have the high value under dense density of Vetiver hedge and high water level inside the reservoir. That value reaches a significant value of 0.4m under density of 530 stem/m^2 and of 50cm water high inside reservoir.

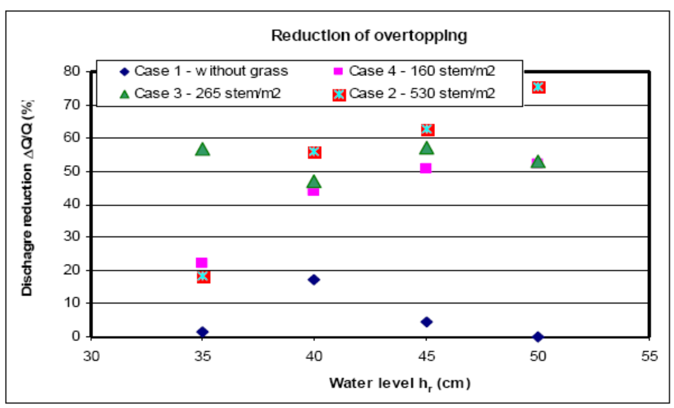

Figure 11: Results of the discharge reduction measurements

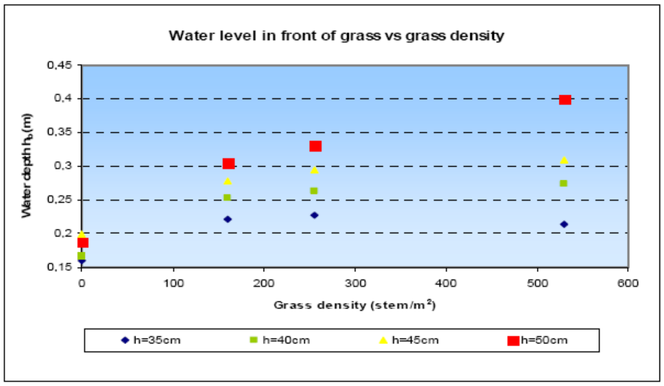

Figure 12: water levels in front of the grass vs. grass densitiy

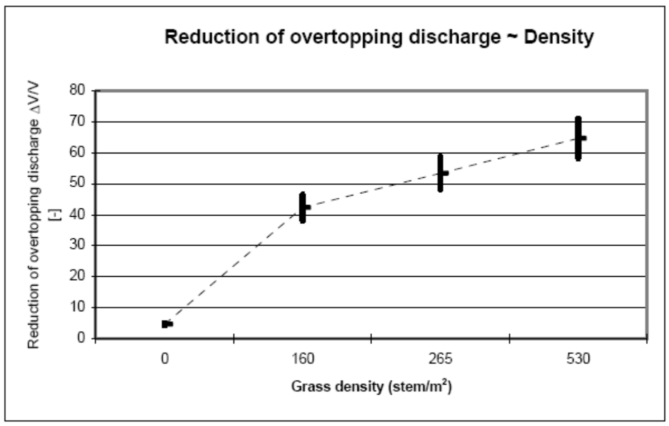

Figure 13: Reduction of overtopping discharge due to a Vetiver hedge

Use in design practice

Planting multiple hedges on an outer slope of a dike might reduce the overtopping by even more than 55%. Hedges can be planted one meter apart to allow people to move between the hedges for inspection and maintenance. Hedges planted near to the still water line will be overtopped by the run-up tongue. These hedges will serve as artificial roughness elements, but will give less reduction than 55%.

The strength of the stems determines whether water will flow mainly through the hedge or flow over the hedge. No systematic research has been done on the failure of mature hedges in flow. In tests in flumes with hedges in stationary flow backwater depths up to 0.4 m. have been reached [Dabney, 1996, Meyer, 2005].

For the layer thickness of the run-up tongue for smooth slopes Schüttrumpf, 2001 finds for regular waves:

$$h = 0.284 \cdot (R_u - z)$$

When the run-up tongue is hitting the hedge, part of it will be reflected and the water level behind the hedge will exceed the thickness proposed by Schüttrumpf, 2001. Therefore, Vetiver grass planted at a height on the outer slope where (R_u-z) is more than 1 meter cannot be expected to reduce the run-up volume by 55%. Vetiver grass planted lower than 1 meter will still reduce the run-up as artificial roughness element but the reduction is less than 55%.

Vetiver grass hedges have to withstand the most damaging waves in a wave spectrum, concerning both overtopping volume and frequency of occurrence. Occasional overloading is not a problem as long as the level of occurrence is low and most of the waves overtopping the dike are reduced by flowing through the hedges. When overloaded the lower 0.4 m. will bend through an elastic range.

Overloaded vetiver hedges planted on the lower parts of the outer slope can still serve as artificial roughness elements. The roughness factor of those artificial roughness elements is not clear. However, Vetiver grass can be much cheaper than stones or blocks and the roughness is much higher than low sod forming grass. So it is beneficial to plant as much hedges as possible. It is not likely that Vetiver grass can cope (with?) the wave impacts of breaking waves. So at the heights where those impacts can be expected a conventional armour layer should be applied.

Example

To illustrate the effect of Vetiver grass hedges on the outer slope on the design of a dike an example is presented. In the Netherlands the following design rule from [Van der Meer, 2002] is used to determine the crest level:

$$\frac{q}{\sqrt{g \cdot H_{m0}^{3}}} = \frac{0{,}067}{\sqrt{\tan\alpha}} \cdot \gamma_b \cdot \xi_0 \cdot \exp\left(-4{,}3 \cdot \frac{h_k}{H_{m0}} \cdot \frac{1}{\xi_0 \cdot \gamma_b \cdot \gamma_f \cdot \gamma_\beta \cdot \gamma_v}\right)$$

With a maximum of:

$$\frac{q}{\sqrt{g \cdot H_{m0}^{3}}} = 0{,}2 \cdot \exp\left(-2{,}3 \cdot \frac{h_k}{H_{m0}} \cdot \frac{1}{\gamma_f \cdot \gamma_\beta}\right)$$

Where:

q	=	average overtopping discharge	(m^3/m per s)
g	=	acceleration of gravity	(m/s^2)
h_k	=	crest level above still waterline	(m)
H_{m0}	=	significant wave height at the toe of the dike	(m)
$\tan\alpha$	=	slope angle	(-)
γ_b	=	the influence of a berm	(-)
γ_f	=	the influence of the roughness of the slope	(-)
γ_β	=	the influence of oblique wave attack	(-)
ξ_0	=	the surf similarity parameter $\xi_0 = \tan\alpha / \sqrt{s_0}$	(-)
s_0	=	wave steepness $s_0 = 2 \cdot \pi \cdot H_{m0} / (gT_{m-1,0}{}^{2})$	(-)
$T_{m-1,0}$	=	spectral wave period: $T_{m-1,0} = m_{-1} / m_0$	(s)

The average allowable overtopping discharge is determined by the state of the inner slope of the dike. In [TAW, 1989] the following average allowable overtopping discharges are proposed:

- 0,1 l/m per s for sandy soil and a bad grass cover
- 1 l/m per s for clay with a reasonable well grass cover
- 10 l/m per s for a good grass cover or an armour layer.

When the still water level in front of a dike is 2.5 m. than the significant wave height can be determined by a rule of thumb: [d'Angremond, 2001] $H_s \leq 0.55 \cdot h$. So the maximum significant wave height is 1.375 m. The spectral wave period is taken 7 seconds.

For a dike with an armour layer of placed granite stones the roughness factor is 0.95. The outer slope has an angle of 1:3 and the average overtopping discharge allowed is 0.1 l/m per second. The crest level then becomes 4.58 meters above the still water level.

Planting one hedge will increase the q to be entered in the formula. An average allowable overtopping of 0.22 l/m per second can now be entered since a hedge will give a reduction of 55%. The crest level then becomes 4.12 meters above the still water level.

Planting a second hedge will give again a reduction of 55% so the allowable q can be 0.49 l/m per second. This leads to a crest level of 3.67 m. The reduction of the overtopping volume will be even more since the amount of water that remains between the hedges is neglected. The hedges have to be planted one meter apart so the second hedge has to be planted 0.3 meters lower than the crest of the dike.

To test whether the second hedge will be overloaded the 1% run-up height is considered. Van Gent, (2002) proposes the following equation for the 1% run-up height:

$$\frac{R_{u1\%}}{(\gamma \cdot H_s)} = c_0 \cdot \xi_0 \qquad for\ \ \xi_0 \leq p$$

$$\frac{R_{u1\%}}{(\gamma \cdot H_s)} = c_1 - \frac{c_2}{\xi_0} \qquad for\ \ \xi_0 \geq p$$

$$c_2 = 0.25 \cdot \frac{c_1^{\ 2}}{c_0} \xi_0 \quad \mathrm{p} = 0.5 \cdot \frac{\mathrm{c}_1}{\mathrm{c}_0}$$

$$for\ R_{u1\%} \quad \mathrm{c}_0 = 1.45 \ \ \mathrm{c}_1 = 5.1$$

In this case the average $R_{u1\%}$ is 4.31 meters. Since the lower hedge is planted at 3.37 m. from the still water line it will not be overloaded by the $R_{u1\%}$. Less than 1% of the waves will overload the Vetiver grass hedges and will be reduced less than proposed. This is considered to be safe. So planting two hedges on the top of the outer slope can decrease the crest level needed by 0.9 m.

The crest level can be decreased from 7.08 m. to 6.17 from the toe. This results in a reduction of the dike volume of 20%. The construction costs can be reduced even more since the costs of labour is often low in developing countries and therefore the use of Vetiver grass is much cheaper than the application of granite stones.

5. CONCLUDING REMARKS

Vetiver grass is a sustainable and innovative solution for the protection of banks. It thrives under a wide variety of conditions. Although the growth rates drop with a high groundwater level it still thrives around the SWL, in contrary with sod-forming grasses. This clearly shows that Vetiver grass can be used at SWL as well as on dikes were the phreatic level can be low.

It is shown that Vetiver grass is able to establish a full-stop of bank erosion caused by rapid drawdown. Therefore it provides us with strong indications that it is highly suitable as an anti-erosion measure. A combination of cohesive soil and Vetiver grass provides the best protection against erosion, which implies that it is highly suitable for banks in delta areas, which consist pre-dominantly of cohesive soil.

A single hedge of Vetiver grass planted on the outer slope of a dike can reduce the wave run-up volume by 55%, in contrary with sod-forming grasses that give no reduction. Planting multiple hedges along the contour of the outer slope might result in even more reduction. The application of Vetiver grass on existing dikes may provide a substantial reinforcement of these dikes.

The advantages of Vetiver grass above conventional methods with the use of stone are numerous:

- Vetiver grass is sustainable. Vetiver hedges of over 100 years old have been found. Vetiver grass is not invasive and no significant diseases are known. Vetiver grass will, in contrary with traditional methods, increase in strength in time.
- Vetiver grass is an economic attractive solution. In most countries in South-East Asia Vetiver grass can be planted for less than $ 3 per meter, while solutions consisting of stone and concrete are expensive in delta areas.
- Vetiver grass allows people to protect their own property. Since the costs are low and it is easy to use local initiatives can be easily achieved.

- Vetiver grass is a well-known bioengineering species. It has been used in many countries for decennia now, and therefore the knowledge on application and maintenance is readily available.
- Vetiver grass can be an aesthetically good solution and is a socially acceptable solution for bank protection.

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