ComCoast WP3

Development of Alternative Overtopping-Resistant Sea Defences
Proposal for Concepts

CUR/RWS

9 May 2005
Proposal
9P8624.C0

A COMPANY OF

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PREFACE

The present proposal deals with a presentation of three potentially feasible concepts for strengthening of the sea defences as to allow for increased wave overtopping, within the framework of ComCoast.
In addition, for each concept an indicative proposal is given for a further theoretical study (Phase 2) and an indicative approach is shown for further testing. This proposal is denoted Phase 1: generation of alternative concepts.

For the present proposal and the activities involved, as well as possible future assignments within Phase 2, a consortium has been formed between Royal Haskoning and INFRAM (Royal Haskoning, being the leading party), the two partners that also participated in the Inventory Study that preceded this proposal. We think that this combination brings about the outstanding expertise from both firms, which we hope is reflected in the present proposal.

The three alternative concepts focus on different types of innovative reinforcement measures, i.e.: reduction of the wave overtopping flow attack, strengthening of the present grass revetments and strengthening of the subsoil.

After an introductory chapter, Chapter 1, the relevant failure phenomena are indicated in Chapter 2. The Concepts A (low hedges), B (application of innovative grass reinforcement) and C (application of Smartsoils® techniques) developed to cope with these phenomena are presented in Appendices A, B and C and are summarized and discussed briefly in Chapter 3. Chapter 4 presents the indicative set-up for the further theoretical studies of Phase 2 for each concept, whereas in Chapter 5 the approach for testing of the concepts is indicated.

The Concepts A and B are highly promising solutions, and we think that they only need limited elaboration and research. The costs are very competitive as compared to the costs for traditional raising of a dike crest (=Reference). The savings can be so big, that further in-depth research on optimization seems anyhow to be useful.
Concept C is still highly experimental for application on sea defences and clayey soils. Nevertheless, it would be an interesting option to further explore

The charm of these Concepts is that they can also be combined in an economical way (A and B together being still much more economical as the Reference) as to cope with increasing Sea Level Rise in future in a flexible way).

CONTENTS

APPENDICES

1 APPRECIATION OF THE PROBLEM AND PROPOSAL APPROACH

1.1 Background and Problem statement

In this proposal the outcome of a reconnaissance of feasible alternative concepts for overtopping-resistant sea defences is presented. This reconnaissance has being carried out within the ComCoast programme, Work Package 3 (WP3). ComCoast is an acronym for ‘Combined functions in Coastal Defence Zones, an innovative concept awarded with European assignment within the InterregIIIb programme.

The proposal has been requested by CUR in a formal request for proposals, dated 5 April 2005. In this request, the principles of ComCoast are summarized and the phasing of the following actions within Work Package 3 is indicated:

- Phase 1: generation of alternative concepts
- Phase 2: theoretical phase
- Phase 3: testing phase

The present proposal deals with the Phase 1.

The alternative concepts are focused on strengthening of the crests and/or inner slopes of the sea defences, as regards increased wave overtopping rates. The concepts should be as competitive as possible compared to raising the defences.
Two locations at the Dutch coast, known as ‘weak sports’ in the coastal defence system, serve as reference pilot locations: the Hondsbossche Zeewering and the Westkapelle Sea Defence.
Basis for the present proposal is the State-of-the art inventory that has been prepared by Royal Haskoning and INFRAM for ComCoast Work Package 3 (Royal Haskoning, 2005[1]), especially to mention the fact sheets on potential reinforcement systems for the crest and inner slope of the defences that have been presented in this inventory.

1.2 Approach

1.2.1 Description of the Concepts

Based on the information of the inventory study and internal brainstorm meetings within the Consortium, three alternative systems have been proposed, which we think will be feasible concepts for reinforcement of the sea defences. The systems are indicated Concepts A , B and C.

The economic feasibility of the alternatives has been assessed roughly against the background of reference costs for raising the defences (the latter while maintaining present low design wave overtopping rates).

The descriptions of the Concepts include an indicative description of the following items (along the lines of the request, in a slightly changed order):

- Description of concept, including the innovative aspects and position w.r.t. the Inventory Study
- Discussion of quality of the concept
- Allowable overtopping (indicative)

[1] Royal Haskoning, 2005: ComCoast WP3, State-of-the-art inventory, commissioned by CUR/ RWS DWW, 9P8624.A0, March 2005.

- Relevant failure mechanisms
- Construction aspects and risks
- Life time expectancy of the concept
- Maintenance aspects
- Indicative impacts on 'LNC' values
- Relevant experience
- Indicative costs for construction & maintenance

1.2.2 Indicative set-up of theoretical phase

This indicative set-up can be seen as a pre-proposal for activities for the Phase 2 and includes:

- Approach: review of activities, resources and duration.
- Cost indication for the theoretical phase per concept.

The set-up will be focused on the aims of Phase 2 (the actual work for this Phase to be commissioned at a later stage, when awarded).
The scope of the theoretical phase includes:

- A technical report, giving a detailed description of the items of 1.2.1
- Preliminary design of the (preferred) concept for the two Pilots mentioned before
- Indication of the permits required and risks involved
- Participation in a testing phase preparation meeting

Obviously, the set-up will be attuned to the views and desires of the ComCoast Project Team at a later stage and, hence, can be subject to adaptation.

1.2.3 Indicative testing approach

Apart from the concepts, as proposed in the present proposal, an indicative approach for testing the concepts will be presented, addressing the broad set-up and scope of the tests, taking into account promotion of the chance of acceptance by all stakeholders.

2 RELEVANT PHENOMENA AND FAILURE MECHANISMS

The Inventory Study focused on a wide scope of ComCoast solutions and phenomena. The present request for proposal, however, has a smaller scope: it will focus on the strengthening of the sea dikes and in particular on two Zwakke Schakels Pilots (‘weak coastal spots’). In strengthening sea defences it should be kept in mind that there is a difference in loading on sea and river dikes and due to that a difference in main failure mechanisms. Innovative systems should be based on understanding of the typical loading phenomena and failure mechanisms involved: this is a prerequisite to prevent failure. If not, there is a danger of developing systems which are not fully effective! In order to develop the right systems for the right failure mechanisms, an overall view is given here on the physical processes which occur at the Hondsbossche Zeewering and at Westkapelle.
The phenomena of wave overtopping is shown schematically in Figure 3.1 and Figure 3.2 indicates the failure mechanisms.

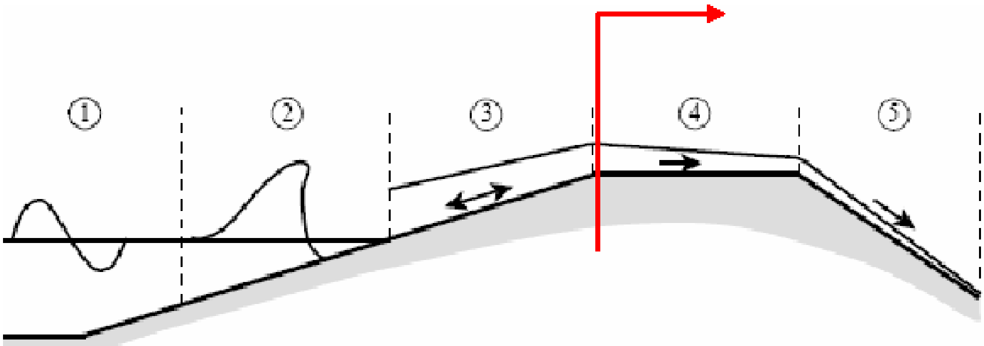

Figure 3.1 Schematical pattern of wave overtopping (area of interest is indicated by the red arrow)

Obviously, both Pilot dikes are sea dikes with severe wave attack. Hence, some of the failure mechanisms as mentioned in the Inventory Study are less relevant for the two Pilots. For instance: floods along river dikes implies water levels close to the crest of the dike and sliding of inner slope and crest, micro instability, piping and uplifting of the hinterland may all be triggered by the large water level difference between the river and the hinterland. All these failure mechanisms are less important for sea dikes, outside of the influence of river flows. In design situations for sea dikes, the design water level will still be some 5 m lower than the crest of the dike. In addition, this design water level remains at that level only for a few hours at the peak of the tide.

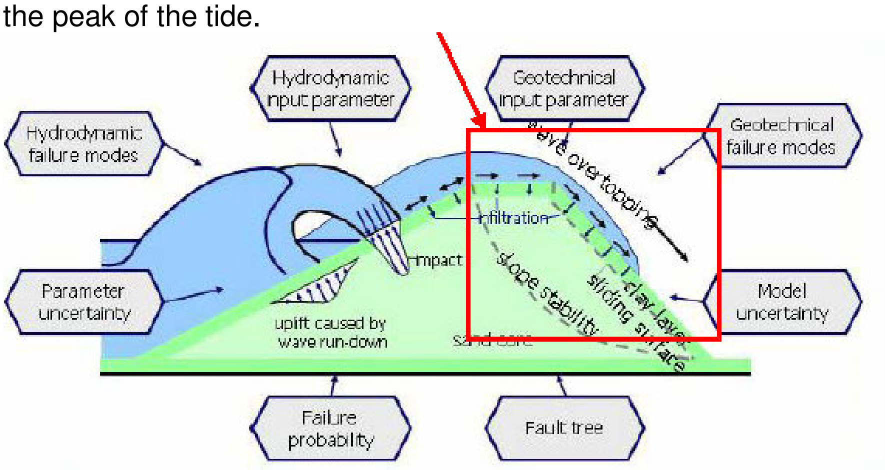

Figure 3.2 Sketch of phenomena and failure mechanisms in wave overtopping

Wave heights at the Hondsbossche Zeewering and at Westkapelle are around 4 to 5 m under design conditions. The waves will break on the seaward slope, more or less influenced by the berm. The wave run-up of the largest waves will be higher than the crest height and this causes the main load: **wave overtopping**. Only a certain percentage of the waves will induce this overtopping, depending on hydraulic parameters and geometry of the dike. Wave overtopping is very often presented as a mean discharge in liters/s per m width. With this measure it is very easy to calculate how much water flows over the crest to the hinterland during a certain storm period. But it is not specific enough for deriving wave forces from it.

The forces on crest and inner slope by wave overtopping occur only for the percentage of waves that really overtops. Each overtopping wave gives a certain overtopping volume (per m width) and has a certain layer thickness on the crest and a certain velocity. It are mainly the high velocities of overtopping water which gives the loads on crest and inner slope. Depending on the overtopping discharge and wave conditions, maximum velocities of 4 to 5 m/s may occur or even higher. The largest overtopping waves will give the largest velocities. The layer thickness of this overtopping flow on the crest will be rather limited: commonly in between 10 and 40 cm.

The main failure mechanism by severe wave overtopping is surface erosion of crest and inner slope. First the cover layer of grass will be attacked. The quality of the root system of the grass and its attachment with the subsoil mainly determines its strength. If the grass would fail, there is still a clay layer underneath the grass cover which may erode further and provides for some residual strength. After erosion of grass cover ánd clay layer, the dike will be close to the situation of an initial breach.

Based on this failure mechanism it is obvious that innovative systems to improve the strength of a dike for wave overtopping should focus on:

- Reducing the load
- Strengthening the grass cover and/or the under laying zone of clay

There is one other failure mechanisms which may play a role. This is penetration of overtopping water through fissures in the cover layer to the core. If enough water can penetrate, it is possible that the inner slope will become unstable and will slide. Whether this mechanism will occur depends mainly on the slope angle of the inner slope and less on the overtopping discharge. Most of the dikes in the 1953 catastrophe failed by this mechanism, but in that situation the inner slopes were often very steep (around 1:1.5). The inner slopes of the Hondsbossche Zeewering and Westkapelse Zeedijk are about 1:3 to 1:3.5. These fairly gentle slopes do not easily slide (this is also the main reason why dike improvements after 1953 have this slope!). Hence, it can be concluded that sliding of the inner slope is a failure mechanism which may not be fully ignored, but as regards the fairly gentle inner slopes of the two dikes this mechanism will probably not play a big role.

3 DISCUSSION OF ALTERNATIVE CONCEPTS

3.1 Introduction

The description of three potentially feasible alternative concepts is enclosed in the Appendices of this Proposal, inclusive of the indicative description items as mentioned in Section 1.2.1.
Hereafter a discussion of the indicative costs of the concepts is given, including construction costs and maintenance. In addition remarks are made on the sustainability of the alternative solutions.

It should be remarked that in case of severe wave overtopping, the area of impact will shift towards the inner crest line and the strongest impact will shift towards the inner slope of the revetment.

A second remark is that we think that natural vegetation can be a stronger revetment than has been anticipated up to now, e.g. in combination with brushwood hedges (that break the wave forces). This follows also from observations of the impact on a vegetated area of large waves generated during (sideways) launching of a vessel in the province of Groningen, 27 January 2005 [2]. In spite of the enormous wave overtopping (with an overtopping rate guessed at 0.5 to 1 $m^3/s/m$), damage to the vegetation did not occur (it should be noted here that this was a ‘solitary wave’ event, that cannot directly be transposed to frequent wave overtopping, so figures are to be handled with care). In addition, the overtopping is calculated at the outer crest line, while the severest flow attack is at the inner crest line and inner slope.

3.2 Discussion on indicative costs for traditional raising of the crest level

The indicative costs of alternative strengthening of the sea defences can be compared to the indicative costs for traditional raising of the crest level. This comparison allows for drawing conclusions about the economic feasibility of the solutions.

The reference costs are the costs incurred in raising the crest level, in order to maintain overtopping at the present overtopping rates.
As a reference, the Hondsbossche Zeewering case has been taken here. In the theoretical phase both Pilots will be considered more in-depth.

The data as presented in the proposal, show that an increase of the design water level of about 0.8 m in 2100 (average scenario) will cause an increase in average overtopping from 2 to 8-10 ltr/s/m, so 4- tot 5-fold (the present figure of 2 ltr/s/m is above the design level of 1 ltr/s/m). Indicative computations with PC-Overslag that we made, showed similar results: 3.2 and 8.1 ltr/s/m for the design water levels of 4.71 m + NAP and 5.51 m + NAP respectively.

It should be remarked that the crest level should usually be raised more than the water level rise, as regards the influence of the outer berm (becoming less effective, when not adapted to the new level) and increased wave heights.

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[2] Royal Haskoning, 2005: Observation of wave overtopping, generated during launching of a ship, commissioned by Rijkswaterstaat DWW, 9R1347.A0, February 2005.

The indicative computations with PC-Overslag also pointed to a progressive increase of crest level as compared to the sea level rise. For the Hondsbossche Zeewering as a conservative figure, a surcharge of 50 % has been taken, resulting in a crest level rise of 1.2 m for the reference situation.

The costs for raising the dike, including costs of reinstalling a grass cover (including a clay layer) can be expressed roughly as total volume of soil required for the enlarged profile times a unit cost per m^3 soil.
The volume can easily be computed, assuming the shape of the dike remaining the same. The indicative unit cost per m^3 soil has been derived from experience gained with the Reference Alternative for Dyke reinforcements (RAD) along the rivers, in which the dikes were anticipated to be raised to cope with increasing floods in future.
The unit costs from the RAD (30 €, without contractor's surcharges) was increased to 35 € to include yearly indexations. The figure taken here is 49 €, including contractor's surcharges (which were adapted to cope with the situation of a sea dike). This cost figure does not include engineering costs, as the costs indication of the alternatives does also not include engineering costs.

The indicative costs for raising the dike (= Reference), with a focus on the Hondsbossche Zeeweering Pilot, can roughly anticipated at 4,000 to 6,000 € per m of defence or at 400,000 to 600,000 € per 100 m of defence (these figures do not necessarily take into account all costs for surcharges and engineering, but should be taken relative to the indicative costs of the concepts).

3.3 Discussion on investment and maintenance costs of the Concepts

For a proper comparison of overtopping alternatives and the reference situation with raised crest, the maintenance costs need also to be addressed. As a first assumption it is assumed that for the reference solution no maintenance is required and that monitoring cost is the same for all solutions. The yearly maintenance costs are roughly guessed and indicated in the Appendices. These have to be capitalized for e.g. a 50 year period (a longer period will hardly add to the capitalized investments costs).
The total costs can be compared now, see Table 2.1.

Table 2.1 Review of indicative total investment costs per 100 m defence

	Construction costs per 100 m defence	**Capitalized cost for maintenance per 100 m defence**	**Total investment cost per 100 m defence**
Reference	500,000	0	500,000
Concept A	40,000[1]	10,000	50,000
Concept B	30,000	0	30,000
Concept C	p.m.	p.m.	p.m.

[1] these costs include a new row of hedges after 25 years.

The costs of Concept C cannot yet be indicated properly and will have to be established at a later stage.
The indicative cost figures show that the costs of the Concepts are highly competitive as compared to raising the defence. Even when Concept A and B are combined, the costs are much smaller than the Reference.

The savings for Concept A and Concept B are so large, that further in-depth research in optimizing these Concepts will probably be highly economical.

3.4 Sustainability

Apart from environmental sustainability, two major points may add to the sustainability of the concepts:
1. feasibility for (gradual) adaptation of the concept for stronger Sea Level Rise (stronger rise than anticipated or longer time horizon)
2. feasibility for combination of concepts.

These points are met pre-eminently in both Concepts. For Concept A additional measures can be taken at a later stage by adding more hedges and a combination with Concept B can also be considered at a later stage. Concept B can also be combined at a later stage with more vegetation, provided that the system is so open that brushwood vegetation is able to develop.
Concept C can also be applied in combination with Concepts A and B.
In this way strengthening of the sea defences may get along with increasing Sea Level Rise in future and an optimum adaptive and flexible solution can be obtained.

4 SET-UP OF THE THEORETICAL PHASE

4.1 Indicative review of activities, resources, timing and budget for Concept A

Activities:
Issues to be investigated further in Concept A are:
1. Hydraulic requirements for the hedge rows
2. Functional requirements for the hedge rows
3. Feasible type of vegetation (type, root system, plantation, trimming)
4. Construction and maintenance aspects
5. Update description of Concept A
6. Preliminary design for the two Pilots
7. Permits and risks

Remark: the hydraulic requirements can be supported in a desk study including the usage of ODIFLOCS (hedge rows to be schematized as roughness elements).

The report will include the following items:
- Detailed description of Concept A
- Preliminary design of Concept A for the Pilots
- Indication of the permits required and risks involved

Apart from that, the Consortium will participate in the testing phase preparation meeting

Resources:
- Consortium: (Royal Haskoning / INFRAM)
- Alterra
- GeoDelft
- WL|Delft Hydraulics

The input of Alterra will be significant; the input of GeoDelft and WL|Delft Hydraulics will be limited to a workshop as outlined below (and if required additional workshops as pro memori items at a later stage).
We suggest to organise a workshop of half a day at the beginning of the activities of Phase 2, in which apart from the Consortium also Alterra, WL|Delft Hydraulics and GeoDelft will participate in order to promote that all available knowledge is included. The ComCoast Project Team can also be represented in this workshop as to allow for optimum transfer of ideas. Information will be sent to the workshop members as a preparation for the workshop.

Timing:
The activities 1-7 of the above can be roughly placed in a time setting as follows, relative to the moment that the job is commissioned (apart from the participation in the testing phase preparation meeting):
- Step 0: preparation/mobilization / issuing info for workshop week 1-2
  workshop: week 3
- Step 1: week 2-4
- Step 2: week 3-5
- Step 3: week 5-6
- Step 4: week 6-7
- Step 5: week 7-8
- Step 6: week 8-10

- Step 7: week 8-10
- Final draft: week 11

Budget indication (based on 1000 € per man day inclusive of all costs, exclusive V.A.T.):

Consortium:	3 man weeks	15.000 €
Alterra:	1 man week	5.000 €
Workshop:	1 man week (including 1 man day per market party)	5.000 €

Without the Workshop the indicative budget required will be 20.000 €. We highly recommend to extend the assignment with the Workshop, resulting in 25.000 €. (useful additional Workshops may be identified at a later stage).

4.2 Indicative review of activities, resources, timing and budget for Concept B

Activities:
Issues to be investigated further in Concept B are:
1. In-depth study on hydraulic aspects of grass reinforcement
2. Exploration of temporary removal and re-installment of the grass sod
3. Selection of feasible type of geotextile meshes
4. Construction and maintenance aspects
5. Update description of Concept A
6. Preliminary design for the two Pilots
7. Permits and risks

Remark: the hydraulic in-depth study involves a further update and review of research on grass reinforcement systems as to arrive at a best guess for overtopping resistance.

The report will include the following items:
- Detailed description of Concept B
- Preliminary design of Concept B for the Pilots
- Indication of the permits required and risks involved

Apart from that, the Consortium will participate in the testing phase preparation meeting

Resources:
- Consortium: (Royal Haskoning / INFRAM)
- Alterra
- GeoDelft
- WL|Delft Hydraulics
- 'Green systems providers'

The input of Alterra will be significant, but somewhat less than in case of Concept A; the input of GeoDelft and WL|Delft Hydraulics will be limited to a workshop as outlined below (and if required additional workshops as pro memori items at a later stage).
We suggest to organise a workshop of half a day at the beginning of the activities of Phase 2, in which apart from the Consortium also Alterra, WL|Delft Hydraulics and GeoDelft will participate in order to promote that all available knowledge is included. The ComCoast Project Team can also be represented in this workshop as to allow for optimum transfer of ideas. Information will be sent to the workshop members as a preparation for the workshop.
In addition, the input of 'green systems providers' (e.g. Flevo Green Support, Zeewolde) will be useful to explore the possibilities for temporary removal and re-installment of the grass sods.

Timing:
The activities 1-7 of the above can be roughly placed in a time setting as follows, relative to the moment that the job is commissioned (apart from the participation in the testing phase preparation meeting):

- Step 0: preparation/mobilization / issuing info for workshop week 1-2
  workshop: week 3
- Step 1: week 3-4
- Step 2: week 4-5
- Step 3: week 4-5
- Step 4: week 5-6
- Step 5: week 6-7
- Step 6: week 7-9
- Step 7: week 7-9
- Final draft: week 10

Budget indication (based on 1000 € per man day inclusive of all costs, exclusive V.A.T.):

Consortium:	3 man weeks	15.000 €
Alterra + Green providers		
	1 man week	5.000 €
Workshop:	1 man week (including 1 man day per market party)	5.000 €

Without the Workshop the indicative budget required will be 20.000 €. We highly recommend to extend the assignment with the Workshop, resulting in 25.000 €. (useful additional Workshops may be identified at a later stage).

The scope of the above can be regarded as a quick survey. We feel that, while the reinforcement measures leave ample room for further innovative and promising developments, a more in-depth and broader reconnaissance will be highly useful. It is our feeling that a larger budget would be sound for Concept B.

4.3 Indicative review of activities, resources, timing and budget for Concept C

Activities:
Issues to be investigated further in Concept C can be indicated now, but cannot be foreseen properly at this time, as regards the highly innovative character of this application on the crest and inner slope of sea defences:

1. Pre-feasibility study on Smartsoils® application on the slope of sea defences
2. Pre-feasibility study of the potential consequences of Smartsoils® on failure mechanisms and residual strength
3. Selection of a potential feasible type(s) of Smartsoils® application
4. Construction and maintenance aspects
5. Update description of Concept C
6. Preliminary design for the two Pilots
7. Permits and risks

Remark: A phasing of this research is recommended, i.e. a ‘go /no go’ decision to be made after step 1 and step 2.

The report will include the following items:
- Detailed description of Concept C
- Preliminary design of Concept C for the Pilots
- Indication of the permits required and risks involved

Apart from that, the Consortium will participate in the testing phase preparation meeting

Resources:
- Consortium: (Royal Haskoning / INFRAM)
- GeoDelft
- Potential Smartsoils® contractor(s)

In this research we will work closely together with GeoDelft.

The activities include a kick-off meeting with GeoDelft at the beginning of the activities; the ComCoast Project Team can also be represented in this kick-off as to allow for optimum transfer of ideas. Potential Smartsoils® contractor(s) will also be invited.

Timing:
The activities 1-7 of the above can be roughly placed in a time setting as follows, relative to the moment that the job is commissioned (apart from the participation in the testing phase preparation meeting):
- Step 0: preparation/mobilization week 1-2
  kick-off: week 3
- Step 1: week 3-6
- Step 2: week 6-8
- Step 3: week 9
- Step 4: week 10
- Step 5: week 11
- Step 6: week 12-14
- Step 7: week 13-15
- Final draft: week 16

A budget indication cannot be made at this point, as the activities cannot be defined properly yet.
A very indicative (and uncertain) guess is:

Consortium:	3 man weeks	15.000 €
GeoDelft:	3 man weeks	15.000 €

, amounting 30.000 € in total.

As a first step, a quick reconnaissance of steps 1 and 2 is recommended, requiring less budget.

5 SUGGESTIONS FOR TESTING APPROACH

5.1 General considerations

The main objective of testing is to prove that the innovative solution can (easily) withstand the prescribed wave overtopping. The first phase in such a programme is to indeed develop and build the solution to its final phase. The theoretical phase in this project will give the basis for the actual development of a solution.

It might be well possible that a solution needs time to arrive at its final strength. This applies to the traditional dike reinforcements (grass seeded at the surface of the added volume of soil), for which it will takes at least one year before the grass has substantial strength and even a few years before the it reaches its full strength. It is well possible that innovative solutions also need some years to gain its final strength when grass cover layers are still applied.

If indeed a solution needs one or more years to develop its strength, this does not mean that this solution is less valuable than others. But is has, of course, impact on the validation programme. First of all such a system should be build on a real dike, preferably on one of the two Pilots or even on both. There are then still different ways of testing, but building this solution in a test facility right from the start is no option as it simply takes too long before testing can start.

Other solutions may gain its strength directly after implementing/construction. These systems could be tested fairly soon after construction.

When a solution has been implemented and gained its final strength, testing should be performed up to and even beyond the specified loads and for the right failure mechanisms. There are a few options depending on the failure mechanism that is considered.

A remark should be placed here as regards the acceptation of stakeholders: field tests are much more convincing than laboratory tests and are to be preferred over laboratory tests where ever possible. In the following, the set-up of field tests is elaborated further.

5.2 Testing approach

The classical way is to test a dike section in a wave flume. As grass and clay can not be scaled only large scale facilities, like the Deltaflume or GWK, can be used. With the GWK in Germany it might be well possible that extra funds can be found in the European Programme Hydrolab. This is not further explored here. With respect to the Pilots of Hondsbossche Zeewering and Kapelle it should be noted that even here the scale will not be 1:1, but more likely 1:3 as the wave heights in reality are in the order of 4 to 5 m, where the facilities are limited to a significant wave height of around 1.5 m. So, the actual situation cannot be tested on full scale!

Moreover, the constructed solution has to be transferred from its original location to the flume. This has been done before for existing grass dikes, but it is a very costly operation.

Finally, only the failure mechanism of erosion of crest and inner slope can be tested, not the geotechnical failure mechanism of water infiltration and sliding of the inner slope. The flumes are simply not wide enough to model this mechanism.

The possible failure mechanism of infiltration and sliding can only be tested on the actual dike and for a sufficient width, for example around 30 m. As velocities of overtopping waves are not the predominant load, but simply the infiltration of water, the classical way for generating overflow may be a good test method here. Tests on overflow have been performed at various locations over the past 30 years. The dike in Flevoland has been the most recent example of this. We propose this method if this mechanism has to be tested.

For the failure mechanism of erosion of crest and inner slope, however, we propose to use the *wave overtopping simulator* (see Figure 5.1 - copyright INFRAM -). This idea has been proposed at other occasions and the copyright rights has been declared by the minutes of the TAW Techniek meeting of 13 March 2001. It is well possible that the idea of the wave overtopping simulator will be developed further within a programme parallel to ComCoast. Next, the idea will be described shortly.

5.3 Wave overtopping simulator

The idea behind the wave overtopping simulator is that:

- All relevant knowledge on wave breaking on slopes and generating overtopping waves is available (TAW 2002: Golfoploop en golfoverslag bij dijken – with the programme PC-Overslag);
- Everything on individual overtopping waves is known sufficiently, such as volumes, distributions, velocities and layer thickness of overtopping water on the crest (work of Van Gent and Schüttrumph);
- Actual waves are not really required to simulate wave overtopping
- The best way to do is to test perform fields tests on a dike.

The idea of the simulator is to make a mobile box to store water and to empty this box at certain times in such a way that it simulates the overtopping tongue of a wave at the crest and inner slope of a dike. Figure 5.1 gives a schematic impression.

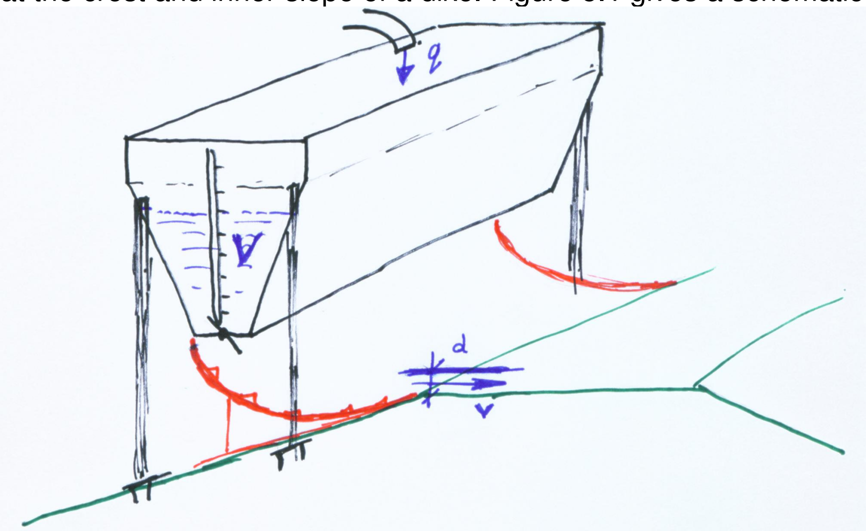

Figure 5.1. Schematic set-up of wave overtopping simulator on seaward side of the dike (copyright INFRAM)

The box will be about 4 m long. The boundary condition is a certain mean overtopping discharge q and this mean discharge is indeed pumped into the box. A maximum discharge of around 50 l/s per m seems feasible (200 l/s pumps), but a discharge of 15-20 l/s per m will usually be sufficient to simulate the wave overtopping in the right way. As soon as the box is filled with a prescribed volume, the valve is opened and water is released on a transition slope to the front of the crest. It is known for each volume what velocity and layer thickness is required at the front of the crest. The transition slope should be developed in such a way that the right velocity and layer thickness is modelled at the front of the crest. Also roughness elements on this transition slope may be required in order to get the right amount of air in the water.

Overtopping volumes in overtopping waves follow a certain distribution. Given the wave boundary conditions and the outer dike geometry, the percentage and number of overtopping waves can be calculated, as well as the distribution of the overtopping volumes. It is this distribution which should be schematized to a fixed number of overtopping volumes and these overtopping volumes should be generated by the simulator.

Figure 5.2 gives an example of such a distribution of overtopping waves. In this case a mean overtopping discharge has been modelled of 1 l/s per m during 6 hours and for a wave height of 2 m. Around 120 waves will overtop in these 6 hours, which means around 20 per hour. The overtopping volumes could be simulated as follows:

56 waves with 50 l per m
40 waves with 150 l per m
10 waves with 400 l per m
6 waves with 700 l per m
3 waves with 1000 l per m

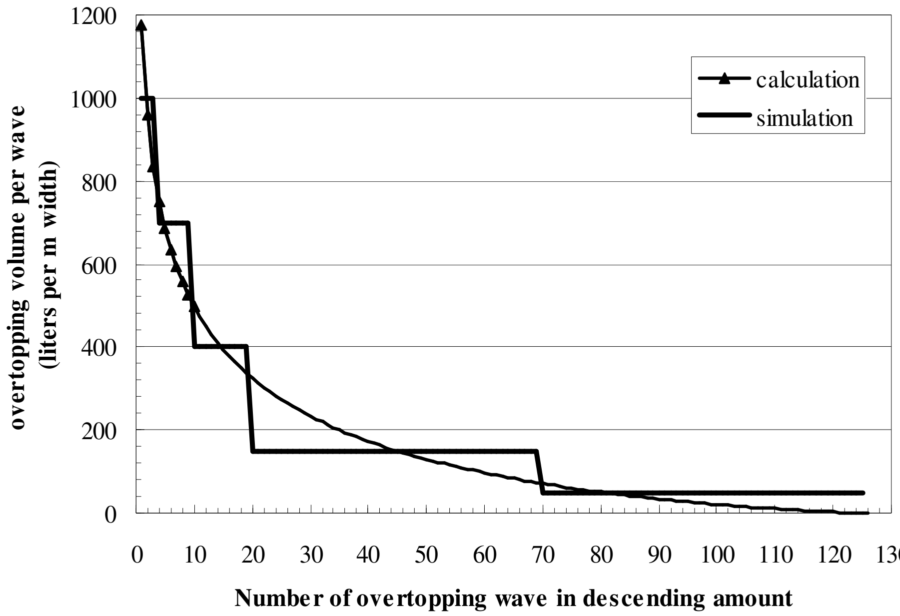

Figure 5.2. Calculated distribution of overtopping volumes and proposal for simulation. Mean discharge q = 1 l/s per m

Of course the volumes should be generated in arbitrary order. Similar graphs can be made for each prescribed overtopping condition. The size of the box determines the maximum overtopping volume which can be generated. The cross-section will probably be in the order of 2 to 3 m^2, giving a maximum overtopping volume of 2 to 3 m^3 per m. It is, however, well possible that a larger mean discharge than 15 l/s per m can be generated, may be up to 50 l/s per m, but the maximum overtopping volume exceeding the size of the box can then not be generated; instead, more volumes with the maximum contents of the box could be simulated.

If the overtopping volume is given, the velocities and layer thicknesses which should be simulated at the front of the crest can be calculated. Figure 5.3 gives this relationship for overtopping conditions of 1 and 10 l/s per m. Velocities of smaller overtopping volumes are around 3 to 4 m/s and for large overtopping volumes up to 6 to 7 m/s. Layer thicknesses are in the order of 0.1 – 0.4 m. These values should be simulated by the overtopping simulator.

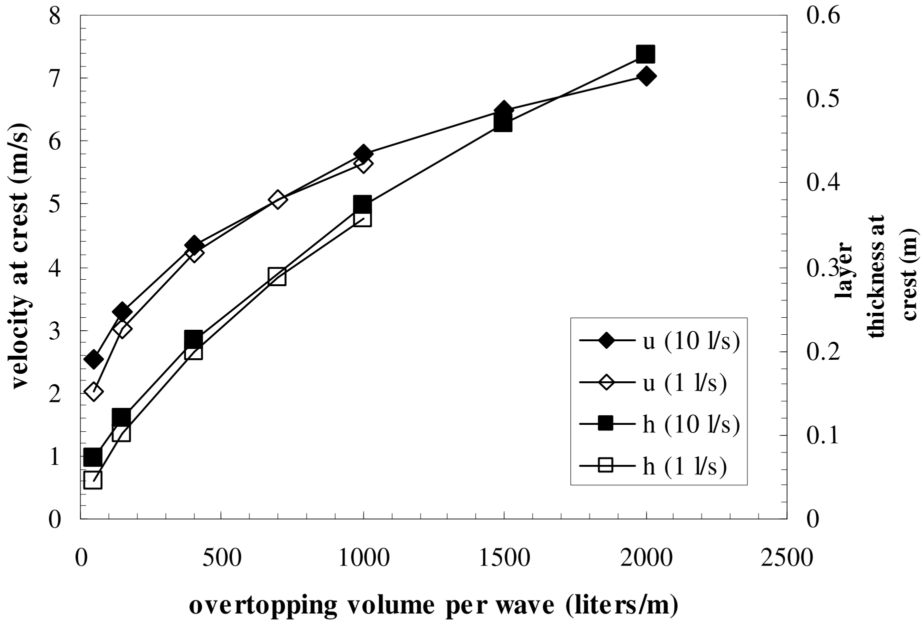

Figure 5.3: Velocities and layer thickness at crest for mean discharges of 1 and 10 l/s per m

Appendix A
Indicative description of Concept A

A1 DESCRIPTION OF CONCEPT A

Concept A is an innovative system, combining the present grass revetment with low local hedges at the crest of the dike and/or just below the crest at the upper part of the inner slope, as shown in the sketch below. The idea is to apply parallel hedge rows (e.g. as can be observed along the Meuse river: the 'Maasheggen shrubs').

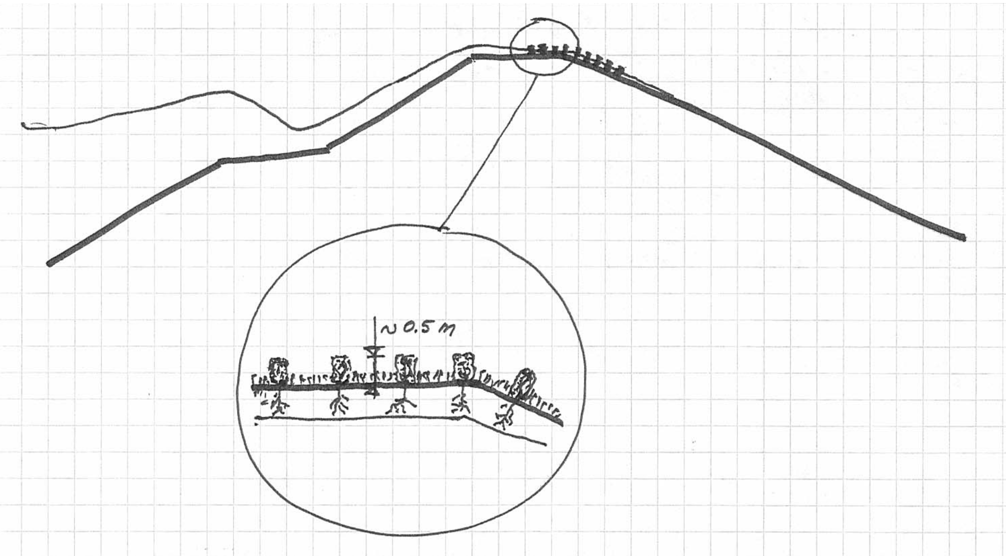

Figure A.1: Schematic representation of low hedges

This is an innovative concept, as up to now vegetation (apart from grass revetments) has not been used at sea defences to mitigate wave overtopping effects and to enhance the stability of the crest and inner slope.

During the theoretical phase the detailed lay-out of the hedge rows will be elaborated further. Special attention should address the density of the branch system of the low hedges (winter time) and the suitability for placement in a coastal environment. An alternative is to shape the hedges during their growth is such a way that a dense row is obtained (like braiding willow twigs). Another possibility is to extend the rows to a continuous broader vegetation, providing a wide strip of hedge type vegetation.

A2 DISCUSSION OF QUALITY OF THE CONCEPT

Objective of the application of the hedges is mainly focused on breaking the force of the overtopping flow due to their flow resistance (when properly placed and with the right type of brushwood).
Another accompanying effect may be the increase the strength of the top layer against surface erosion over the area where the hedges are placed due to their strong root system (provided that they are of the right vegetation type).

A3 ALLOWABLE OVERTOPPING (INDICATIVE)

The allowable overtopping for Concept A is, obviously, not known. However there are two reasons that may add to a rather good overtopping resistance:

1. The basic revetment is the present grass revetment: this system is commonly applied and it is widely acknowledged that the grass revetment is much more robust than presently considered in safety assessments.
2. The hedges added to the grass revetment aim to have a overtopping flow breaking effect and possibly add to the strength, as outlined in the above.

These considerations pinpoint to an overtopping resistance that can be fairly good.

Another indication comes from the observations during the waves generated during the launching of the vessel as mentioned in Section 2.1. These waves hit a vegetated area (grass, small brushwood and small trees) with guessed peak flows of more than 0.5 m^3/s/m and no damage was observed.
The possible overtopping flow rate will be in the same order of magnitude, when 15 ltr/s/m will be taken as a mean future overtopping rate. Assuming an effective duration of 6 s during severe wave overtopping and the subsequent overtopping volume 3 m^3, the maximum flow rate will be about 0.5 m^3/s. In addition, overtopping tests in the Deltaflume showed that even higher overtopping rates could be applied without damage to the grass revetment (it must be remarked that this revetment was in very good condition, however).
In all, we think that Concept A may be feasible for coping with the increased overtopping rates as mentioned for the Pilots.

A4 RELEVANT FAILURE MECHANISMS

Failure mechanism are essentially the same as for the present defence systems, as no ‘hard’ structural and geometrical changes are introduced. The failure mechanism of surface erosion will not be as critical as in the present situation, as the momentum of the overtopping flow rate is reduced and possibly also the strength is improved at the location where the brushwood is applied.

A5 CONSTRUCTION ASPECTS AND RISKS

Construction is fully nature oriented (landscaping) and at a very modest scale; hence, no major equipment is required and the risks will be low. Attention should only be placed at the right moment of plantation and care should be taken as to avoid trampling the existing grass cover during construction.

A6 LIFE TIME EXPECTANCY OF THE CONCEPT

Life time expectancy can be rather large for brushwood, dependent on the type of hedges and the environmental conditions. Yet it is rather simple to replace the hedges by young plantation in due time, as to maintain the efficacy of the improved revetment system.

A7 MAINTENANCE ASPECTS

Maintenance will be required, as to maintain the brushwood in a good shape. By proper selection of the type of brushwood, maintenance can be limited to occasional trimming as to limit the height of the shrubs. In addition, timely replacement of the hedge rows is required.
Vandalism does not seem to be a major threat as hedge rows are natural elements that do not 'invite' for vandalism.

A8 INDICATIVE IMPACTS ON 'LNC' VALUES

Impacts on LNC values can generally be considered as neutral or positive, as regards the natural application with brushwood for strengthening the defence. Moreover it is believed that the landscaping can be done in such a way that the visual impact is limited and done in an optimal way, may be even adding to the landscape values. The original vegetation (grass revetment) will not be reduced and additional vegetation (brushwood) will give increased natural values.
The construction is essentially natural and will hardly intervene in the environment.

A9 RELEVANT EXPERIENCE

There is ample experience with a variety of hedge plantations. However, using them for breaking wave flows at a primary defence is not a known application as far as we know. Hence, this aspect needs further exploration during the theoretical phase.

A10 INDICATIVE COSTS FOR CONSTRUCTION & MAINTENANCE

Indicative cost figures are rather uncertain, because the proper hedge row vegetation has yet to be selected. Assuming average cost figures, and a lifetime of 25 years, two times in 50 years the hedges have to be constructed. The capitalized costs have been assessed roughly at about 40,000 € per 100 m length of the sea defence, assuming a crest width of 3 m and a inner slope length of 12 m (in total 15 m) up to the inner berm (referring to the Hondsbossche Zeewering).
The maintenance costs deal with yearly trimming and are roughly assessed at 500 € per 100 m of defence. Capitalized over 50 years this effort amounts to about 10,000 € per 100 m of defence.
Hence, total investment will be in an order of magnitude of 50,000 € per 100 m of defence.

Appendix B
Indicative description of Concept B

B1 DESCRIPTION OF CONCEPT

Concept B is a system, in which the grass revetment is strengthened by applying reinforced systems. The character of these systems is that they have some additional coherence and at the same time allow for vegetation growth. Reinforced systems are widely available. However, the innovative part here is to apply a system that is optimally improving the stability, while at the same time, remaining the character and functions of the grass revetment as much as possible.

Systems of this type are as mentioned in the Fact Sheets of the Inventory (Royal Haskoning, 2005). The innovative part of is to apply a system in which the grass sods can be removed, e.g. with a thickness of 5 cm, and be replaced after the reinforcement measure has been applied. The reinforcement measure may consist of a very open geotextile mattress system ('meshes'). An impression is shown in Figure B.1

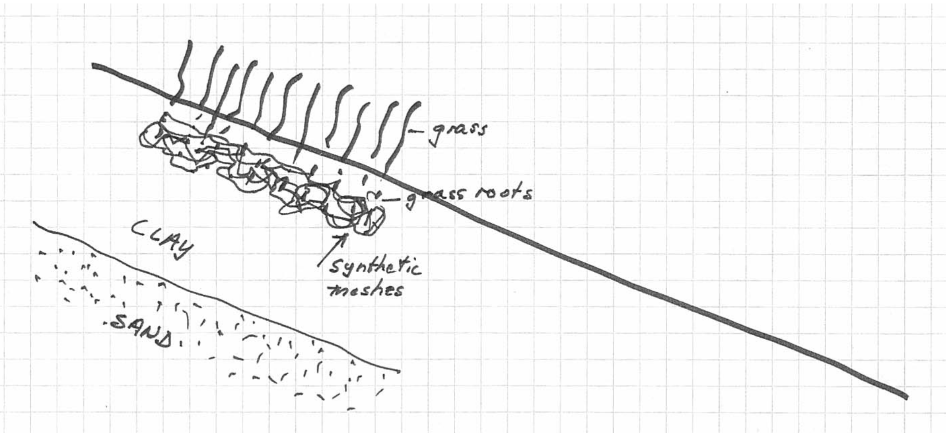

Figure B.1: Cross section of a reinforced grass revetment

During the theoretical phase the most appropriate reinforcement system needs to be elaborated further, with special reference in improving the natural failure mechanism of the grass/clay system. A challenge is to select or develop a system that is practically invisible, easy to apply in combination with a good economy. The performance of synthetic meshes should be compared at these points to the performance of open concrete revetments. Innovative aspect is to avoid seeding after application of the reinforcement system e.g. by temporary removing and reinstalling the grass cover layer.

B2 DISCUSSION OF QUALITY OF THE CONCEPT

Improvement of the flow and wave overtopping resistance needs to be done by improvement of the root/substrate consistency, as regards the failure mechanisms. Smart-soil techniques (bacterial improvement of consistency) cannot be applied easily as these may harm the grass vegetation (apart from improvements to better contain the moisture). Hence, mechanical strengthening needs to be applied, e.g.: non waven fabric meshes, pins, open concrete mattresses, etcetera.
Utterly, reinforced grass revetments can be applied in a practically invisible way. Sometimes (e.g. for fabric meshes) the reinforcement can be covered with a thin soil layer so the functions of the grass (grazing, negotiability) may remain unaltered. In this sense a reinforced grass revetment might be addressed as a 'reference alternative'.

B3 ALLOWABLE OVERTOPPING (INDICATIVE)

Allowable overtopping rates are known from investigations on reinforced grass revetments for ‘green’ reservoir spill ways. These investigations (e.g. Hewlitt, 1987[3]) show that current velocities (steady state) can be endured of 3 to 4 m/s over 10 hours of attack for fabric mesh systems.

B4 RELEVANT FAILURE MECHANISMS

Quite much is known about the failure mechanism of a grass revetment. Failure occurs by dislocation of parts of the grass revetment, including parts of the root/clay substrate. By introducing the reinforcement, the integrity of the grass sods, including the root substrate, is improved. Failure will, therefore extend deeper soil layers and may more resemble the failure mechanism of micro-instability than of surface erosion. A point of attention is that the reinforcement should not increase the risk of micro-instability.

B5 CONSTRUCTION ASPECTS AND RISKS

Reinforcement implies the application of a reinforcement structure at or below the soil surface. Consequently, the grass vegetation (sods) needs to be taken away temporarily and reinstalled afterwards. This requires careful handling and construction outside of the storm season. We think that risk can then be reduced to acceptable levels.
In consultation with an outstanding firm in handling grass sods, Flevo Green Support, the possibility of using so-called ‘big rolls’ was discussed. The method of working involved is to cut the existing grass sods at a certain thickness, roll them on a reel with assistance of a tractor and unroll them after placement of the meshes and soil filling. The only restriction in using the ‘big rolls’ is the requirement for a coherent grass sod. Seeding new grass is less attractive, as it will take a considerable time before a good grass cover is obtained again (this may take some years). Fabric meshes may be applied by reinstalling the grass sods after placement of the meshes and filling with soil. A innovative challenge would be to apply a system in which the present grass cover need not to be taken away, e.g. by introducing synthetic pins.

B6 LIFE TIME EXPECTANCY OF THE CONCEPT

The life time expectancy is high when synthetic materials are applied. By their hidden presence, synthetic reinforcement systems may not be exposed to direct sunlight and thus will not be subject to UV ray deterioration.

B7 MAINTENANCE ASPECTS

Maintenance will normally not be required, apart from replacement of the system after its lifetime.
Vandalism will not be a threat as grass reinforcements are practically not removable or portable.

[3] Hewlett, H.W.M. et al., 1987: Design of reinforced grass waterways.
CIRIA, Report 116, ISBN: 0305-408X.

B8 INDICATIVE IMPACTS ON 'LNC' VALUES

The impact on LNC values are practically nil, as compared to the present grass revetment, when the systems can be made invisible by the vegetation. The latter may be a prerequisite and the typical landscape value of grasses embankments will then not be affected. Allowance for larger burrowing animals will be impeded, but this may not be seen as a drawback as regards safety (e.g. muskrats). Generally stated, the LNC impact can be practically nil.
During construction, dependent on the type of reinforcement system, some disturbance may occur by working equipment, but this will be small when the equipment remains small scale (this can be an asset in selecting the appropriate system).

B9 RELEVANT EXPERIENCE

A feasible geotextile mattress, that is produced in the Netherlands and that has a performance record for similar situations, is the mattress of Enka (Enkamat) 7220 with a very loose, three dimensional structure. This type of Enkamat has been applied successfully at small spillways in Sussex en Gloucestershire (U.K.), which are overflowed several times a year.
The firm Flevo Green Support has ample experience (e.g. the field in the 'Amsterdam Arena' soccer stadium and on golf greens) with replacing grass sods using the so called 'big rolls'. This firm has indicated the possibility to roll and unroll grass sods at a sloping terrain with a length of 15m and a with of about 1 m by cutting the sod at a thickness of 4 cm.

B10 INDICATIVE COSTS FOR CONSTRUCTION & MAINTENANCE

Construction costs for a reinforced grass revetment can be roughly guessed at 15 to 20 € per m^2, or say 300 € per m of defence (Royal Haskoning, 2005[1]). It should be remarked that in the latter reference removal of the existing cover layer was envisaged. Here, this will be just temporarily ('big rolls') and it is assumed that these costs compensate. Hence the costs for 100 m of defence are roughly guessed at 30,000 €.

Appendix C
Indicative description of Concept C

As Concept C is still very experimental, the description of the aspects below is partly hypothetical and subject to further study in Phase 2.

C1 DESCRIPTION OF CONCEPT C

Concept C deals with the strengthening of layer underneath by means of application of the so-called Smartsoils® technique. This is especially useful for very strong grass covers that exist on a sandy-clay type of under layer. Such a 'poor' clay layer is in itself not very flow resistant. Upgrading of this resistance by means of Smartsoils® techniques will result in a good back-up stability, in case the grass cover fails. Concept C, as indicated in Figure C.1, can be considered as a very innovative system.
Photograph C.2 shows the erosion pattern in a clay layer that is not reinforced by Smartsoils® techniques (GWK flume, Germany).

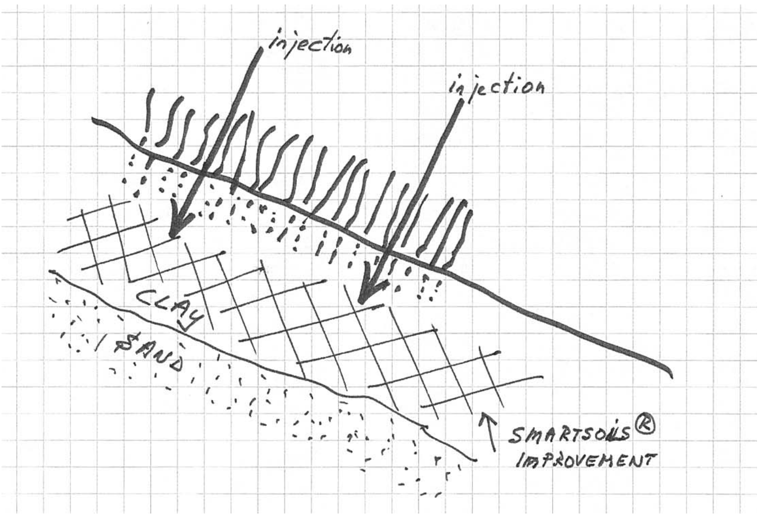

Figure C.1: Schematic presentation of Smartsoils® application

Photograph C.2: Pattern of clay erosion by wave overtopping

The concept of Smartsoils® is based on bacterial improvement of the consistency of the soil. The idea of using microbe activity to strengthen the soil has been invented by GeoDelft. However, Smartsoil® techniques can possibly (this assumption still has to be checked) not be applied to the top soil of the dike revetment as they may harm the grass vegetation (apart from improvement to better contain the moisture). Therefore injection of the 'bonding agent' to the under-laying clay layer is needed. Instead of using bacteria to improve the consistency of the clay-layer also other techniques (e.g. grout injection) are feasible, referring to the INSIDE innovations. However, INSIDE applications aim at reducing the risk of macro-instability, whereas here the erosion resistance of the clay layer, as well as micro-stability, are meant to improve.
Experience with Smartsoil® techniques for sandy soils and peat show very promising results. For clayey materials this experience is not yet gained, but in case of sandy clays there is a possibility for reinforcement by means of Smartsoil® techniques (to be elaborated further).

Concept C has not been introduced earlier in the Inventory Study.

C2 DISCUSSION OF QUALITY OF THE CONCEPT

By improving the consistency of the clay layer of the dikes crest and inner slope, the resistance against wave overtopping will become better. In case surface erosion of the grass layer takes place, by which this layer is 'lost', the under-laying sandy clay layer will act as a 'hidden defence'.
Because of the high level of consistency of the 'improved' sandy clay layer, further erosion will be retarded or will even not continue further.
Advantage of the concept is the fact that the functions of the grass (grazing, accessibility) may remain unaltered and that this is a fully 'hidden' solution.

C3 ALLOWABLE OVERTOPPING (INDICATIVE)

The allowable overtopping for this concept is not known, since it is a method still under development, which has not yet been applied in this manner. The resistance of the 'reinforced' clay layer against progressive erosion is anticipated to be high (this to be checked by tests).

C4 RELEVANT FAILURE MECHANISMS

Failure mechanisms are essentially the same as for the present defence system. By the improvement of the strength, the progressive erosion of the clay layer after failure of the grass revetment (by dislocation of grass sods) is expected to at least slow down or to halt completely.
A point of attention is the risk of micro-instability that is not allowed to increase because of the applied reinforcement by means of injections. At the other hand, the risk at micro-instability may in itself be reduced by the improved soil properties.

C5 CONSTRUCTION ASPECTS AND RIKS

A great advantage of this concept is the fact that the grass vegetation doe not need to be taken out because of the use of the injection method. This method can be compared to the way farmers nowadays inject the manure of their cattle with special manufactured injection machines.

Attention should be paid to depth and the grid of the injections. The depth must be sufficiently beneath the grass revetment as it may otherwise harm the grass vegetation. The grid must be small enough to realise a clear interface with the root zone of the grass.

C6 LIFE TIME EXPECTANCY OF THE CONCEPT

As we are dealing with a new approach (in case of using bacterial activity) to strengthen the dikes crest and inner slope it is not yet possible to predict the life time expectancy. Research by GeoDelft may give further clues in due time.

C7 MAINTENANCE ASPECTS

Maintenance will normally not be required, apart from repeating the injection after its lifetime.
Vandalism will not be a threat as we are dealing with a fully ‘hidden’ protection.

C8 INDICATIVE IMPACTS ON ‘LNC’ VALUES

The impact on LNC values will be nil as compared to the present grass revetment, as the system is invisible underneath the existing grass vegetation.
During construction some disturbance may occur by working equipment, but this will be small scale compared to the machinery needed for traditional dike improvement.

C9 RELEVANT EXPERCIENCE

The use of Smartsoils® to strengthen the top layer of the dikes crest and inner slope is a highly innovative concept. The effect of using bacteria to strengthen the soil is a proven concept, but the utilization of this technology is still under development. Under the right conditions bacteria can produce calcite ($CaCO3$) which is the crystalline material that binds together natural limestone. While these bacteria make calcite inside a soil matrix, the calcite cements the sand grains together, and a subsoil is formed which becomes much stronger and stiffer. The application of ‘poor’ clayey soils is still under research.

C10 INDICATIVE COSTS FOR CONSTRUCTION & MAINTENANCE

The construction costs for a reinforced top layer of the dikes crest and inner slope by using Smartsoils® is highly dependent on the used grid in which injection takes place, the specific conditions and on the needed quantities of ‘bonding agent’ and cannot be properly assessed at this moment (to be delayed to Phase 2).
Maintenance costs are highly dependent on the life time expectancy of the concept, but we anticipate that these costs will be low. During the lifetime of the concept itself no supplementary maintenance is needed if compared to the present grass revetment as long as the improvement is effective.