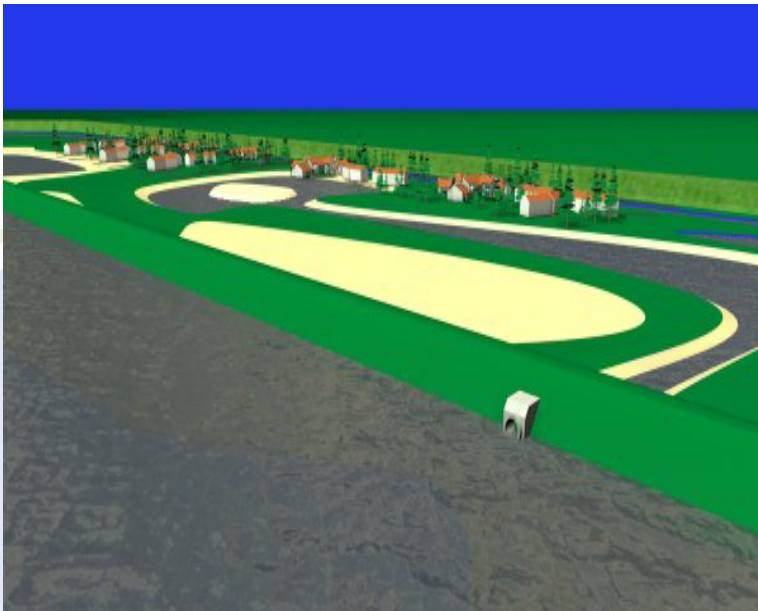


State-of-the-art inventory

ComCoast WP 3



A small blue icon of a wave or coastline to the left of the main title.

State-of-the-art inventory

ComCoast WP 3

This report has been prepared by Royal Haskoning

The ComCoast project is carried out in co-operation with ten partners.

- Rijkswaterstaat (NL - leading partner)
- Province of Zeeland (NL)
- Province of Groningen (NL)
- University of Oldenburg (D)
- Environmental Agency (UK)
- Ministry of the Flemish Community (B)
- Danish Coastal Authority (DK)
- Municipality of Hulst (NL)
- Waterboard Zeeuwse Eilanden (NL)
- Waterboard Zeeuws Vlaanderen (NL)

**This report is an initiative of the ComCoast project, co-financed
by the EU-Interreg IIIb North Sea Programme.**



Work package 3 Civil engineering aspect

State-of-the-art Inventory

Final Report

Acknowledgement:

This report is a deliverable of WP.3: "Civil engineering aspect"

The work is performed by Royal Haskoning

The report is written/edited by K.A.J. van Gerven and G.J. Akkerman, Royal Haskoning

List of important contributors to the input of this report:

Preface

The present report provides a state-of-the-art inventory of relevant information and technical concepts for the ComCoast project, being the first phase of the research stages of Work Package 3 (WP3). This project was assigned to Royal Haskoning by CUR.

The information scan was set-up in a systematic way. About 160 relevant references have been traced for technical aspects and related projects. These references have been presented in a table database, including a preliminary judgement of the relevancy of these references for ComCoast. Further references can be introduced to the database in subsequent phases of ComCoast WP3.

Based on the information, a preliminary evaluation was made for related projects.

Emphasis was put on a preliminary evaluation of potential protection systems for the inner slope of primary sea defences (embankments). To this end, an illustrative evaluation methodology has been presented in this report. As an illustrative outcome, a reinforced grass revetments showed a high score and therefore this system seems to be adoptable as a feasible system for strengthening of the crest and inner slope of overtopped defences. Other types of protection systems have been presented as well and are briefly indicated in the Fact Sheets attached to this report.

Prior to further elaboration of the most appropriate strengthening systems in subsequent phases of WP3, the development of an 'overall judgement framework' is recommended as a follow-up of the present methodology. This framework should not be limited to the stability of the protection system only, but should also include other failure mechanisms for overtopped embankments, with special emphasis on critical soil mechanical failure mechanisms.

As regards the new field of application (strengthening of crest and inner slope of embankments under increased wave overtopping), there may be room for new and innovative systems to reinforce the defences, together with methods to reduce tidal impacts and wave overtopping. It is recommended to promote further innovative research within subsequent phases of WP3.

Information

Information on the ComCoast project can be obtained through the Project Management, located at the Rijkswaterstaat in the Netherlands.

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1. Introduction

1.1 About this report

In the present report the outcome of the state-of-the-art inventory on the Technical Reconnaissance of ComCoast, Work Package 3 (WP3), is presented. ComCoast is an acronym for 'Combined functions in Coastal Defence Zones, an innovative concept awarded with European assignment within the InterregIIIb programme.

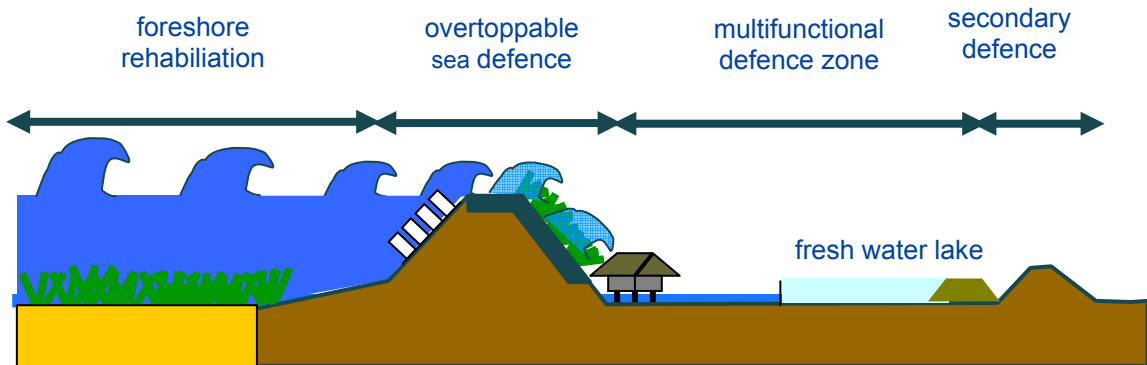


Figure 1.1 Schematic representation of the ComCoast concept

ComCoast seeks to find an answer on future problems in the coastal defence zones associated with climate change effects (sea level rise, increase of wave attack, increase of downpour intensities) and subsidence of coastal drainage areas (e.g. the Dutch polders). As a consequence, the coastal defences will be attacked more vigorously in future. Maintaining safety levels in future is a key issue, as to safeguard protection for living, working, recreation and the environment. Traditionally, for embankments the response is to raise the defence crest levels (combined with adaptation of the crest and slopes). However, ongoing heightening of the defences introduces more uncertainty and the long-term economy may be doubted. ComCoast aims to develop more sustainable long-term solutions. These solutions can be sought in different directions:

- Measures to reduce wave attack at the defences are for instance: foreshore recharge, foreshore wetland restoration, wave breaking defences, defence berm structure;
- Measures to limit wave overtopping e.g. by placing rough elements at the outer slope and crest of the defence, wave deflection walls;
- Measures to strengthen the defences and at the same time allow for more overtopping and overflow by adapting the adjoining hinterland so as not to increase the height of the defences.

A practical observation is that at present, some 'dyke sections' in the Netherlands do not meet the requirements for limited wave overtopping. Rejected sections will further increase by the future problems associated with climate change and subsidence. ComCoast seeks to offer solutions to this problem as an alternative to raise the dykes.

This state-of-the-art inventory is the first phase of the range of WP3 activities, aiming at adequate design criteria and innovative design approaches of (more) heavily overtopped sea defence structures (embankments, dunes are not considered). Increased allowance of overtopping of sea defences is the basic idea within the ComCoast concept. In this inventory, however, also the other solutions mentioned above are shortly addressed.

The present report gives background information on the state-of-the-art (with the focus on technical and practical items) and presents and discusses the most relevant concepts. Apart from the technical aspects, a short inventory of ComCoast related projects has been carried out.

This report includes the following items: Chapter 1 (Introduction), in which the outline and assignment of the report is indicated and the approach is shortly dealt with.

In Chapter 2 (Information retrieval) the scanning methodology is briefly treated, together with the database set-up. Chapter 3 presents the scanning results.

Based on the information found, a review of projects related to ComCoast is given in Chapter 4, as well as its relevance for ComCoast. In Chapter 5, a review of concepts for reinforcement of sea defences is presented and a preliminary evaluation of suitable concepts for ComCoast is presented. Conclusions and recommendations are given in Chapter 6. In the Annex A, 'fact sheets' of (potentially) feasible solutions are included, showing more details on specific concepts. Annex B contains a printout of the database.

It should be noted here that new, innovative solutions are not included in this inventory, as the inventory is focused on existing concepts, solutions and knowledge; the development of innovative solutions is an activity within ComCoast that is scheduled at a later stage.

1.2 Study assignment and acknowledgements

The study was assigned to Royal Haskoning by the CUR / Rijkswaterstaat DWW following a call for an e-mail proposal by Ir. J.P. Koenis of CUR dated 3 September 2004 and based on the proposal by Royal Haskoning with reference 9P8624.A0/L001/GJA/RVBE/Nijm dated 14 september 2004.

In this study, Royal Haskoning joined with an outstanding expert on sea defences, Dr. J.W. van der Meer of INFRAM.

Royal Haskoning greatly acknowledges the fruitful and stimulating co-operation of the Client's representatives, especially to mention the WP3 Project Team and the Users Group.

1.3 Approach

The present state-of-the-art inventory of WP3 deals with tracing information relevant for ComCoast. To this, information has been gathered from world-wide sources and this information has broadly been scanned on relevant items. In-depth analysis of the information is not included in the state-of-the-art, as this is part of a subsequent phase of activities in WP3, including the detailed study of information and innovative concepts. The information scan is laid down in a digital table, from which different kind of compilations can be obtained.

The subjects to be covered do include the physical elements and major phenomena of the ComCoast concept, as well as flood risk management aspects of similar concepts. More specifically to mention:

- Inventory of flood risk management experience in similar concepts, e.g. based on relevant items from other research programs: e.g. VNK (up-to-date safety assessment in the Netherlands), the application of inundation areas in Belgium and relevant European projects as ComRisk (coastal defence risk), FraMe (flood risk management in estuaries DELOS (Environmental Design of Low Crested Coastal defence Structures), CLASH (Crest Level Assessment of coastal Structures by full scale monitoring, neural network prediction and Hazard analysis on permissible wave overtopping).
- Inventory of the technical state-of-the-art of overtopped defences and relevant technical items within the adjoining (multifunctional) wetland area.

The VNK project is valuable in its field, but concentrates very much on the methodology for safety assessments. Interesting result up to now is that piping seems to be an important failure mechanism for sea defences, although the calculation rules have been adapted as regards the over-estimation of piping. The outcome of VNK may in due time, fuel the discussions on safety levels of the primary defences.

The focus of the inventory is on the last item, as regards the scope of WP3.

The set-up of the study, intermediate and final results have been thoroughly discussed within the WP3 Project team as well as with the representatives of the Users Group, the latter during a special workshop in which the relevance to ComCoast of the retrieved information was analysed.

2. INFORMATION RETRIEVAL

2.1 Scanning methodology

Scanning of relevant information was done based on well-chosen key words. The following key-word information (see table 2.1) was considered to be essential for the search.

The approach to the scan and the database set-up has been done in consultation with an information expert of Royal Haskoning, Mr Harry Rombout and a database expert Mr Willem Kroonen. The scan is being done with assistance of the Royal Haskoning library, in which also paid information (e.g. articles from the SWETSCAN system) are introduced. As they are not free of charge, only first level information (see further) will be introduced to the database.

Some preliminary searches with the Google search engine have been carried out to sustain the key word groups (see table 2.1), in such a way that the number of postings was nor nil, nor very large.

The searches have been done from four sources:

- internet scans (search engines Google, 'Google+' (RH-system), Kennisbank Waterbouw, etcetera)
- specific library scans (SWETSCAN, RWS-LIS, TUD library)
- research programmes (VNK, COMRISK, FraMe, DELOS, CLASH)
- personal bibliographies

The strategy is to identify relevant records and to include these in the database only when relevant for ComCoast.

Free information is gathered in order to explore the characteristics of the information. When just a summary or even less became available, but the information seems to be relevant, e.g. in case of the SWETSCANS, the information is preliminary rated as relevant or not relevant based on this limited information (this is indicated in between brackets as to show the preliminary character of this rating).

Table 2.1: Review of the key words used for the retrieval of relevant information.

COMCOAST search key words	
major key words	first addition
	state-of-the-art
	possible additions
primary / secondary 'sea defence'	regeneration
	rehabilitation
coastal bufferzone / catchment area	sustainable
	innovative (concept)
multifunctional 'sea defence'	coastal (sea)(defence)
	coastal zone management
(controlled) inundation (areas)	controlled flooding
	environmentally friendly shoreline
spatial functions' in 'coastal areas'	storm conditions
(artificial) (inland) wetlands / salt marshes	
operational management tidal / coastal wetlands	
beach nourishment & wave reduction	
coastal or tidal inlet / outlet structures	
(coastal) dike / dyke revetments & overflow / overtopping resistance	
multifunctional space & sea defence	
wave overtopping / overflow	
salt water intrusion / salt water prevention	
reinforcement of embankment(s) (structures)	
operational management coastal wetlands	
realignment & sea defence	
watermanagement & tidal drainage or storage	

2.2 Database set-up

As outlined in the above, the database has been set-up in table format. Under the Windows XP professional system, this format is fully compatible with ACCESS and other Windows table formats. Hence, at a later stage, the table can easily be imported in ACCESS, as to allow for typical database searches and selections (this was not done within this project however).

The database itself has free records, in case no prescribed synopsis can be given, e.g. reference or essential focus. However, records with selection boxes ('picklists') are introduced as much as possible, as to allow for proper database searches and selections. Background information on the records are given in 'comment boxes' (red indicator) on top of the database.

Major efforts have been put into the right set-up of relevant information blocks. This has been done at two levels.

- The first level: containing concrete (objective) information;
- The second level: containing other information: e.g. link to ComCoast subjects, availability, type of knowledge, relevance and the essential focus.

The fields above are shown in the figure below.

Table 2.1: The different information blocks used in the ComCoast database (with the contents of the pick-lists) for both first and second level information

COMCOAST DATABASE	
First level information:	Second level information:
Type of information: A) technical data B) spatial / planning examples	Link COMCOAST subjects: A) Foreshore wave reduction B) Overtopping / overflow C) Strengthening of the defense D) Control structures E) Wetland/retention area F) Secondary defense G) Salt water intrusion
Title (of the book / project etc.):	
Author:	Availability: A) Yes; book or report B) Yes; digital C) Payable but free abstract D) Payable and no free abstract E) Not retrievable
Research framework (e.g. TAW, CLASH etc.)	
Reference (e.g. internet site or ISBN number):	
Country: A) Netherlands B) Germany C) U.K. D) Denmark E) Belgium F) Other	Type of knowledge: A) Theoretical B) Hypothetical C) Proven/practical
Location (e.g. U.S.A., north sea coast etc.)	Relevance: A) ++ B) + (+) C) 0 (0)
Date (year):	
	Essential focus : (e.g. wave transmission, wetland restoration etc.)

As can be seen in Table 2.1 distinction has been made between two types of information:

- Spatial / planning examples (i.e. projects relevant for ComCoast)
- Technical data (technical research and applications).

One of the ComCoast participating countries is selected from the pick-list in the information block 'country' in case of one of the following situations:

- A record is directly related to a specific project in one of the countries participating in the ComCoast project.
- The reference of the record is a book or report published in one of the countries participating in the ComCoast project.

If a record has no direct connection with one of the ComCoast participating countries the option 'other' is chosen from the pick-list in the information block 'country'. The information block 'location' is in this situation used to define the specific country (e.g. U.S.A).

The relevance of the different records is finally rated by taking in account several considerations:

- The actuality of the record.
- Overall relation with the ComCoast concept.
- Essential results and type of knowledge.

When from a record not enough information is available to make a clear assessment, e.g. in case of the SWETSCANS, the information is preliminary rated as relevant or not: this is indicated in between brackets as to show the preliminary character of this rating.

Within the context of the present inventory, the database will only be partly filled. It can be anticipated that in the subsequent stages of the ComCoast research, much more information will become available (e.g. from the partners). With this information the database can easily be updated, which will add more value to the database.

3. SCANNING RESULTS

3.1 General results

In the database more than 160 potentially relevant sources have been identified. Many more sources were traced but they were judged to be not relevant at first sight.

Not all sources could be made available in hardcopy or digitally, hence some had to be judged by a short description of the contents only or e.g. by scrutinizing the internet site.

The relevance has been identified based on both the actuality of the subject/research and the connection with the ComCoast concept. The relevancy score has been limited to ++, + and 0, as items that are not relevant (- and --) are not included in the database.

It should be remarked that paid information has not always been included yet. This also applies for specific information of the partners. Hence, a future update might be useful at a later stage, e.g. when the focus can be restricted more towards some highly relevant subjects for ComCoast. Such an update can be anticipated at the next stage(s) of WP3, in which feasible concepts for sea defence reinforcements will be developed.

In addition, the present database table may be extended into a more user-friendly database (e.g. to be placed at a ComCoast internet site).

A hard copy of the table database is given in Appendix B attached to this report.

3.2 Results of inventory on similar projects

Real projects that are identified or already have been carried out and that might be relevant for ComCoast projects, are identified with the type denotation 'spatial/planning examples'.

The number of potentially relevant projects is rather limited. A part of the general table from Appendix B is shown hereafter in Table 3.1.

The sequence of the information is set at relevance, going from ++ to 0.

A majority of scans refer to the 'wetland/retention area' category and these scans are judged to be relevant (+). The most relevant scans (++) are located in the 'coastal zone' category. Information is basically on wetland development and on wave reduction measures and do refer to hypothetical cases or theory, rather than to real schemes.

An excellent reference at this subject is the inventory within ComCoast, including schemes that have already been implemented in the UK (Costin, 2004).

A further analysis of these and other concepts is being presented in Chapter 4.

Table 3.1: Review of projects relevant for ComCoast

FIRST LEVEL INFORMATION							
#	NAME / TITLE / PROJECT	AUTHOR / BENEFICIARY	REFERENCE	RESEARCH FRAMEWORK	COUNTRY	LOCATION	DATE
1	Towards sustainable flood and coastal management. Identifying drivers of, and obstacles to, managed realignment, foreshore recharge and regulated tidal exchange. A literature review for the	Laure Ledoux et al	www.elsevier.com/locate/landusepol	Socio-Economics	U.K.		2004
2	Managed realignment, foreshore recharge and regulated tidal exchange. A literature review for the	Gemma Coslin	Draft copy, oct 2004		U.K.		2004
3	Een brede waterkering, van concept naar praktijk	N. Bakker	Afstudeerrapport, TU Delft 2003		Netherlands	Zeeuws-Vlaanderen	2003
4	Markemeer. II. Bewezen sterkte met betrekking tot geotechnische toets	J.W. van der Meer, J. Wouters en L.P. Schouws	Infram report t221	Interreg and EU	Netherlands	Inner lake (Markemeer)	2000
5	COMRisk	J. Hofstede - coordinator	www.comrisk.org		Other	North Sea coast	2004
6	Integrated ecological-economic model for the Waddensea	J.L. de Kok, H.G. Wind and N. Keizers	www.infram.nl_products&services_publications		Netherlands	Waddensea	1998
7	Ein Decision Support System für das Flussreinzugsgebiets-Management der Elbe	S. Kofalk, M. Scholten, S. Boer, J.L. de Kok, M. K.	www.infram.nl_products&services_publications		Germany	Elbe	2004
8	Effects on soft bottom assemblages	Anonymous	DELOS: Repts D18, D33, D34 and D45	DELOS			2002
9	Effects on epibionta	Anonymous	DELOS: Repts D35, D38 and D46	DELOS			2002
10	Effects on mobile fauna and human usage	Anonymous	DELOS: Repts D14, D15 and D16	DELOS			2002
11	Large scale effects of breakerwater spatial arrangements	Anonymous	DELOS: Repts D29, D39, D40 and D47	DELOS			2002
12	Ecological modelling of breakerwater impacts	Anonymous	DELOS: Repts D48, D49, D50 and D51	DELOS			2002
13	Extracting a cost-benefit transfer function from CV studies	Anonymous	DELOS: Report D11	DELOS			2002
14	Case studies on monetary valuation of environmental changes	Anonymous	DELOS: Report D28	DELOS			2002
15	Ramsar Handbooks for the Wise Use of Wetlands	Ramsar Convention Secretariat	www.ramsar.org	Convention on Wet	Other	Switzerland	2004
16	Assessment of hydraulic restoration of San Pablo marsh, California	Grimsar, M.E.	Environmental Monitoring and Assessment 98 page 69-92		U.S.A.		2004
17	Risk assessment Haute Gironde	J.W. van der Meer, P. Weidema	Infram reports 11010		Other		2002
18	Prototype observations and hindcasting	Anonymous	DELOS: Repts D12, D25, D30, D52 and D58	DELOS		Grande, France	2002
19	Cumulative effecten van kustingrepen, quick scan naar morfologische en ecologische effecten van	A.A. Arends, H.J.E. Erenstein	www.rivm.nl/natuur/kustrapport/2003/nr/z2003042.html		Netherlands		2003
20	A Modern Integrated Stormwater Management Concept for a Complete River System	Eikehard Pfeiffer	ASCE: Urban Drainage 2002: Global Solutions for Urban Drainage		Germany	Essen	2002
21	Restoration of coastal habitats. To the benefit of birds, plants or loads?	U.S. Andersen	Littoral 2002: The changing coast. EUROCOAST / EUCC, Porto, H		Other	Denmark	2002

SECOND LEVEL INFORMATION						
COMCOAST SUBJECTS						
#	1	2	Availability	Type of knowledge	Relevance	Essential focus (keywords)
	p	p	p	p	p	p
1	COASTAL ZONE	WETLAND/RETENTION AREA	yes: digital	proven/practical	++	realignment
2	COASTAL ZONE	FORESHORE WAVE REDUCTION	yes: digital	hypothetical	++	literature review
3	COASTAL ZONE		yes: book or report	hypothetical	++	realignment
4	STRENGTHENING OF DEFENCE	OVERTOPPING/OVERFLOW	yes: book or report	hypothetical	+	proven strength
5	STRENGTHENING OF DEFENCE		yes: digital	proven/practical	+	risk analysis, failure mechanisms
6	WETLAND/RETENTION AREA	SALT WATER INTRUSION	yes: digital	hypothetical	+	decision support systems
7	WETLAND/RETENTION AREA		yes: digital	hypothetical	+	decision support systems
8	WETLAND/RETENTION AREA		yes: digital	hypothetical	+	ecological assessment
9	WETLAND/RETENTION AREA		yes: digital	hypothetical	+	ecological assessment
10	WETLAND/RETENTION AREA		yes: digital	hypothetical	+	ecological assessment
11	WETLAND/RETENTION AREA		yes: digital	hypothetical	+	ecological assessment
12	WETLAND/RETENTION AREA		yes: digital	hypothetical	+	ecological assessment
13	WETLAND/RETENTION AREA		yes: digital	hypothetical	+	economic assessment
14	WETLAND/RETENTION AREA		yes: digital	hypothetical	+	economic assessment
15	WETLAND/RETENTION AREA		yes: digital	hypothetical	+	economic assessment
16	FORESHORE WAVE REDUCTION		yes: book or report	proven/practical	+	salt marsh
17	OVERTOPPING/OVERFLOW	WETLAND/RETENTION AREA	yes: digital	hypothetical	0	risk management flooding
18	FORESHORE WAVE REDUCTION		yes: digital	hypothetical	0	prototype data
19	COASTAL ZONE		yes: digital	hypothetical	0	policy
20	WETLAND/RETENTION AREA		payable but free abstract	proven/practical	0	water management
21	WETLAND/RETENTION AREA		yes: book or report	hypothetical	0	ecological impact

3.3 Results of technical aspects

In Table 3.2 below, only highly relevant scans are shown and the sequence is set at the ComCoast subjects. From this it is shown that the majority of the postings is of the 'overtopping/overflow' category, next 'foreshore wave reduction' and finally 'strengthening of defence'. This sequence is typical for the state-of-the-art of the knowledge.

Foreshore wave reduction is a topic that has been studied extensively. Still, some knowledge gaps have to be filled in, as regards the complex nature of wave reduction.

The same applies for reduction of wave overtopping by measures at the outer slope and the crest of the defence structure. Here, new innovative solutions might be introduced to combine excellent stability performance with wave run-up reduction.

The information retrieved provides a good basis for further in-depth examination.

In an ultimate situation, the ComCoast defence shifts towards a breakwater type of structure. Although this will generally not be realistic, yet information on breakwater overtopping is included in the database (e.g. from DELOS programme), as to provide a means to provide a target for extrapolation.

During increased wave overtopping and overflow, the crest and inner slope of the embankments are more heavily attacked. For the reference situation, i.e. grass revetments, knowledge seems to be abundant, but the general position is that the time averaged value of the maximum allowable overtopping rate (1 l/s/m) is much smaller than what the grass revetment can cope with prior to failure (probably tenfold as high). It is likely that even more margin can be gained by combining the grass revetment with other types of vegetation, or by reinforcing the grass revetment with open geosystems. The latter is dealt with in Chapter 5.

A further analysis of the technical aspects related to ComCoast is being presented in Chapter 4.

Table 3.2: Review of technical aspects relevant for ComCoast projects

#	NAME / TITLE / PROJECT	AUTHOR / BENEFICIARY	REFERENCE	RESEARCH FRAMEWORK	COUNTRY	LOCATION	DATE
1	Design of Streambank Stabilization with Geotext Reinforced Earth Systems	Bruce M. Phillips	ASCE Joint Conference on Water Resource Engineering and Water		USA		2000
2	Gesdiken: aanvullende analyse van de waterbeweging op het binnentalud	M. Klein Breieler en G.M. Smith	WL Delft Hydraulics rapportnummer H 1991		Netherlands		1996
3	Alternatieve open taludbekledingen, samenvattend verslag	Waal, J.P. de	WL Delft Hydraulics, H 1930		Netherlands		1998
4	Dijkdoornakken, ontstaan, voorkomen en bestrijden	Gerwen, K.A.J. van	TU Delft, 2004. Afscheurrapport sectie Waterbouwkunde		Netherlands		2004
5	Design of reinforced grass waterways	H.W.M. Hewlett et al	CIRIA report 116, 1987. ISBN 0 86017 285 6 / ISBN 0305-408X		U.K.	London	1987
6	Coastal erosion in Nam Dinh province, Red River delta, Vietnam	Wijdevan, B.	TU Delft, M.Sc.thesis, Delft University of Technology, October 2002		Other	Vietnam	2002
7	Technisch Rapport Golfoploop en Golfvoering bij Dijken	J.W. van der Meer	www.waterken.nl	TAW	Netherlands		2002
8	Wave Run-up on and Wave Overtopping over a Prototype Rubble Mound Breakwater	Blom Van der Waaij et al	ASCE: Ports 2001, America's Ports - Gateways to the Global Economy		Other	USA, Virginia	2001
9	Wave run-up and overtopping on smooth and rough slopes of coastal structures	Shankar N.J., Jayaramine M.P.R.	Ocean Engineering 2003; ISSN 0029-9018	CLASH	Netherlands	Singapore	2003
10	Quantification of measurement errors, model and scale effects	A. Kortema	CLASH, Report D40	CLASH	Netherlands	Pratten	2004
11	Short time measure to decrease overtopping on the Hondsbossche Zeezuwering	Hooftmeesterschap Hollands Noorderkwartier	Royal Haskoning	CLASH	Netherlands		2004
12	Prediction method, Neural network modelling of wave overtopping at coastal structures	M. Klein Breieler and G.M. Smith	WL Delft Hydraulics report H1991	CLASH	Netherlands		2004
13	Gesdiken. Aanvullende analyse van de waterbeweging op het binnentalud	B. Poozela, M.R.A. van Gent, H.F.P. van den Bogaard	CLASH, Report D42	CLASH	Netherlands		1996
14	Wave overtopping flow on seedlings - experimental and theoretical investigations	H. Schutttrumpf	PIANC bulletin T14, pp. 7-23		Germany		2003
15	Layer Thicknesses and Velocities of Wave Overtopping Flow at Seadikes	H. Schutttrumpf	Submitted to Journal of Coastal Engineering		Germany		2004
16	Wellenberaufströmung an Seedeichen	Schutttrumpf H., Oumeraci H.	ISSN 0017-7504		Germany		2001
17	Low exceedance wave overtopping events. Measurements of velocities and the thickness of water	Gent, M.R.A. van	www.library.tuelft.nl/idref/cluuster / DC 030202PH803	Delft Cluster	Netherlands		2002
18	Database on wave overtopping measurements on the Zeebrugge rubble mound breakwater	Pfeifer Troch	Coastal Engineering 91 (2004) 609-628. www.elsevier.com/locate/co		Belgium	Zeebrugge	2004
19	Database on wave overtopping at coastal structures	H. Verhaeghe, J.W. van der Meer, G.J. Steendam	www.library.tuelft.nl/idref/cluuster	CLASH	Netherlands		2003
20	Residual strength after initial failure by overtopping	Knoeff J.G. et al	www.niranam.nl/products/services/publications	Delft Cluster	Other		2003
21	Wave transmission behind row-crested structures	R. Engelen, J.W. van der Meer, M. Buchini and S. Vidi	Estuaries, coastal and shelf science (1989) 49, 411-426		U.K.		1989
22	Wave transmission over sea marshes. A field and numerical modelling study from North Norfolk	M. Wolter et al	ETDR 2002, Coastal Zone Management		Germany		2002
23	Field observations and their importance in coastal zone management	J.W. van der Meer, M. Wolter, E. L. et al	Shankar N.J., Jayaramine M.P.R. Ocean Engineering 2003		Germany	Spain	2003
24	Numerical model to estimate the propagation of random breaking and nonbreaking waves over dunes	J.W. van der Meer, B. Wang, A. Wolters, B. Zan	www.tuelft.nl/idref/cluuster/products/services/publications		Other		2004
25	Wave wave transmission over coastal structures	Acronymus	DELOS, Report D53	BELOS			2002
26	Empirical, ecological and socio-economic input to design guidelines	Acronymus	DELOS, Report D59	BELOS			2002
27	Formulation of guidelines for multi-purpose design	Acronymus		BELOS			2002

COMCOAST SUBJECTS							
#	1	2	Availability	Type of knowledge	Relevance	Essential focus (keywords)	
1	STRENGTHENING OF DEFENCE	OVERTOPPING/OVERFLOW	payable but free abstract	proven/practical	++	reinforced earth systems	
2	STRENGTHENING OF DEFENCE	yes: book or report	yes: book or report	theoretical	++	overflow and strength	
3	STRENGTHENING OF DEFENCE	yes: book or report	yes: book or report	theoretical	++	open taludbekledingen	
4	STRENGTHENING OF DEFENCE	yes: book or report	yes: book or report	theoretical	++	failure mechanisms	
5	SECONDARY DEFENCE	yes: book or report	yes: book or report	proven/practical	++	design low-crested structures	
6	OVERTOPPING/OVERFLOW	yes: book or report	yes: book or report	proven/practical	++	waves and strength of dikes	
7	OVERTOPPING/OVERFLOW	payable but free abstract	payable but free abstract	proven/practical	++	wave run-up and overtopping	
8	OVERTOPPING/OVERFLOW	payable but free abstract	payable but free abstract	proven/practical	++	wave run-up and overtopping	
9	OVERTOPPING/OVERFLOW	yes: digital	yes: digital	theoretical	++	scale effects	
10	OVERTOPPING/OVERFLOW	yes: digital	yes: digital	proven/practical	++	roughness outerflank flood defence	
11	OVERTOPPING/OVERFLOW	yes: digital	yes: digital	proven/practical	++	prediction method overtopping	
12	OVERTOPPING/OVERFLOW	yes: book or report	yes: book or report	hypothetical	++	overtopping velocities	
13	OVERTOPPING/OVERFLOW	yes: book or report	yes: book or report	hypothetical	++	overtopping velocities	
14	OVERTOPPING/OVERFLOW	yes: digital	yes: digital	proven/practical	++	overtopping velocities	
15	OVERTOPPING/OVERFLOW	yes: digital	payable but free abstract	proven/practical	++	overtopping velocities	
16	OVERTOPPING/OVERFLOW	yes: digital	yes: digital	proven/practical	++	overtopping	
17	OVERTOPPING/OVERFLOW	yes: digital	yes: digital	proven/practical	++	overtopping	
18	OVERTOPPING/OVERFLOW	yes: digital	yes: digital	proven/practical	++	overtopping	
19	OVERTOPPING/OVERFLOW	yes: digital	yes: digital	theoretical	++	overtoppin database	
20	OVERTOPPING/OVERFLOW	yes: digital	yes: digital	theoretical	++	overflow and strength	
21	FORESHORE WAVE REDUCTION	yes: digital	yes: digital	proven/practical	++	wave transmission	
22	FORESHORE WAVE REDUCTION	yes: digital	yes: digital	proven/practical	++	wave reduction	
23	FORESHORE WAVE REDUCTION	yes: book or report	yes: book or report	theoretical	++	wave damping	
24	FORESHORE WAVE REDUCTION	yes: book or report	yes: book or report	theoretical	++	wave damping	
25	FORESHORE WAVE REDUCTION	yes: digital	yes: digital	proven/practical	++	chlique wave transmission	
26	FORESHORE WAVE REDUCTION	yes: digital	yes: digital	hypothetical	++	chlique wave transmission	
27	FORESHORE WAVE REDUCTION	yes: digital	yes: digital	proven/practical	++	guideline	
28	FORESHORE WAVE REDUCTION	yes: digital	yes: digital	proven/practical	++	guideline	

4. REVIEW OF COMCOAST RELATED PROJECTS

4.1 Approach

The inventory of ComCoast related projects and (non-technical) aspects did not bring many references, which is logical as regards the innovative concept of ComCoast.

A very useful reference is the literature review for ComCoast referring the UK experience on ComCoast concepts (number 2 in the list: Costin, 2004). Although this experience cannot be transferred directly to most locations in Belgium, the Netherlands and Germany, the UK experience with managed realignment, foreshore recharge and regulated tidal exchange is very useful. Hence, this item will be addressed further in this chapter. Prior to this, two relevant MSc theses have been produced that focus on the implications of introducing wide coastal defences. These are discussed as well.

Another item of interest, although more indirectly related to ComCoast, is retention basins for reducing the flood levels in the Scheldt basin in Belgium: some of these 'controlled inundation areas' have already been completed within the FraMe programme, other are planned.

A remark should be made here as regards the difference between 'overflow' and 'wave overtopping'. Overflow has extensively been studied (last stages of vertical closure dams, flow over low dams), and is nearly stationary. In contrast, at coastal defences wave overtopping will occur by (near) maximum waves out of the wave spectrum and, hence, is a strongly intermittent and unsteady phenomenon. The significance of information on overflow is only of importance for ComCoast, when this information is also related to the strength behaviour of embankments.

Prior to the discussion on the information in the above, a brief review is given of relevant ComCoast subjects.

4.2 ComCoast options

In this section we first zoom in at the ComCoast approach, as indicated in the Work plan of WP3 (with some small adaptations), to provide a reference framework. Starting point is that the loads at the dyke will increase in future (increased water level, tidal action and wave action).

First, the traditional approach is outlined (A), next the creation of a seaward defence zone (B), the creation of a wide landward defence zone (C), and the shift of the primary defence zone landward by abandonment of the primary defence (D) are indicated. It should be noted that the options can be combined.

A. Traditional approach: Reduction of overtopping (dyke geometry adaptation)

Point of departure is that hardly any water will overtop the dyke during increased attack, in order to prevent the inner slope to become unstable. The inner slope mostly consists of a (not reinforced) grass revetment. Maintaining wave overtopping within acceptable limits for this 'single line sea defence' can be done in several ways:

- Raising the dyke crest or mounting obstacles on the crest (e.g. sheet piles).
- Reducing the wave run-up, for instance by adapting the cross section (e.g. slope angles, berm geometry) or increasing the roughness for wave run-up at the outer slope.

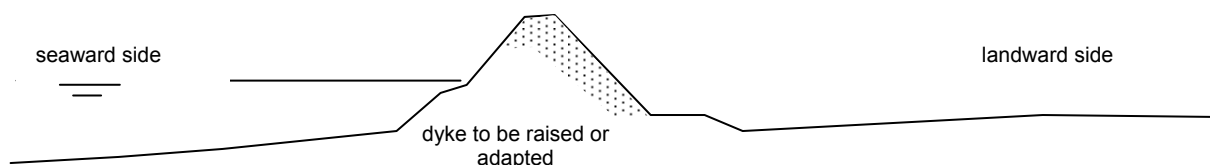


Figure 4.1: Traditional response to increased loads (increased overtopping is not allowed)

B: ComCoast: Wide defence zone seaward: reducing the (increased) hydraulic loads on the primary sea defence

Starting point here is to reduce the increased loads by adaptations of the seaward zone:

- Depth reducing measures
Measures to reduce the depth (such as sand banks) at the seaward side of the dyke will cause the waves to break during severe storms. In the UK, for instance, recharge schemes are carried out in front of coastal dykes.
- Low-lying reclamation dykes, like in Friesland and Groningen, Ost Friesland (Germany) and Ellewoutsdijk (the Netherlands), act like breakwaters during extreme storms. The wave impact on the main sea defence decreases.

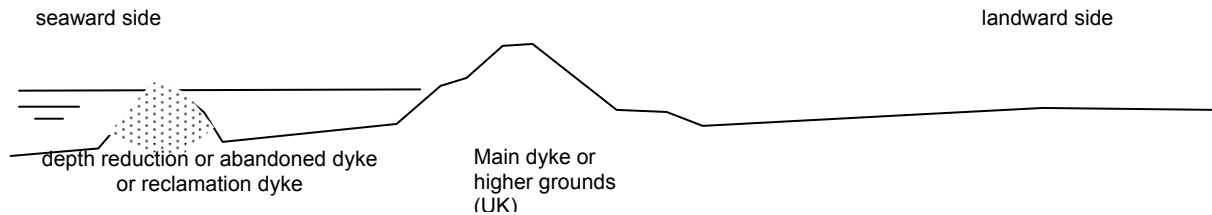


Figure 4.2: ComCoast with wide defence zone seaward (increased overtopping is not allowed)

C. ComCoast: Wide sea defence zone landward: coping with increased loads by increasing the strength of the dyke and handling the incoming water

Starting point is that the primary dyke is fully stable against increased overtopping during severe storms, without raising the crest. The overtopped sea water will be handled in the coastal zone at the landward side of the dyke. This can be done in several ways, depending on the local circumstances:

- The water can be drained sufficiently.
Possibly the water management system in the polder has to be adapted to be able to handle the overtopping water. In this case there is no inundation of originally dry land.
- The water cannot be drained sufficiently.
The overtopping water has to be stored during extreme storm situations in the wet coastal zone. Existing higher ground levels close by, or secondary dykes can be used to prevent the dry hinterland from getting inundated.

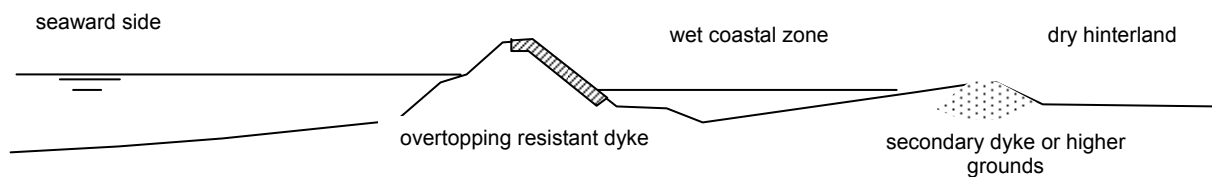


Figure 4.3: ComCoast with wide defence zone landward (increased overtopping allowed)

- Tidal control sluice
Additionally to the above, a control sluice with a culvert in the main dyke may be used to discharge the surplus of overtopped water after the storm. This culvert may also be used to provide controlled tidal exchange in daily circumstances. It will be closed during severe storms to guarantee the safety.

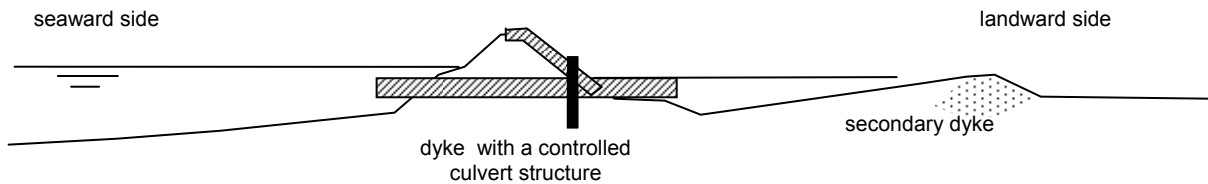


Figure 4.4: ComCoast with wide defence zone landward (increased overtopping allowed) and control of excess water and /or daily tidal exchange (Regulated Tidal Exchange)

As can be seen from the above, the hinterland area may act as a multifunctional coastal zone, in which salt water functions can be restored in accordance with freshwater functions (dependent on the water management goals), thus creating salt, brackish and fresh water wetlands. This wetland zone may be arranged to accommodate different spatial functions: e.g. nature, sea-farming (shellfish, fish, seaweed), recreation, compensatory habitats, etcetera. This enables to create a multifunctional and flexible and economical sea defence zone. In order to achieve maximal synergy, participation of central, regional and local authorities, as well as entrepreneurs and environmental organisations is necessary.

D. ComCoast: Wide sea defence zone landward with a shift of the primary defence towards the hinterland: abandonment of the primary defence

Starting point is that the primary defence will not be needed anymore in future to cope with increased loads. Instead, the primary defence will be partly opened or even fully removed to allow the tidal action in the landward defence zone. The primary defence is shifted landward and can be effected by (upgraded) secondary defences or by higher grounds. In the wide zone, there will be a sheltering effect by the tidal flats and by the remains of the original primary defence, hence the loading at the hinterland is less than on the original primary defence.

- Managed Realignment
Controlled abandoning of the sea defence by creating a tidal inlet in the original dyke and building a new dyke at the landward side of the original dyke. The original dyke will give shelter against wave impact and tidal impact.

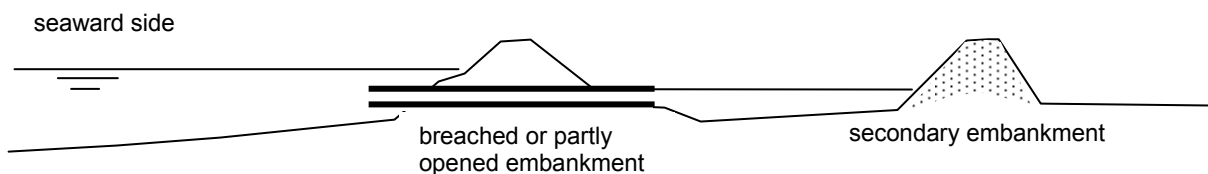


Figure 4.5: ComCoast with abandonment of primary defence function

4.3 Discussion of related projects

4.3.1 UK literature review for ComCoast related projects [Costin, 2004]

In the UK, coastal flood management is very active and focuses on several items: flood risk mapping, counteracting developments in foodplains, coastal protection and promotion of coastal flooding in areas that are presently protected (managed realignment).

The latter issues are addressed in the inventory that has been carried out on managed realignment, foreshore recharge and regulated tidal exchange. Schemes have already been carried out in estuaries along the east coast of the UK, i.e. at the Salcott (Abbots Hall Farm) and Blackwater (Orplands Sea Wall) estuaries.

A sketch of managed realignment is shown in Figure 4.6, while in Figure 4.7 a controlled breach is shown in the Orplands Sea Wall.

Landward restoration of saltmarsh

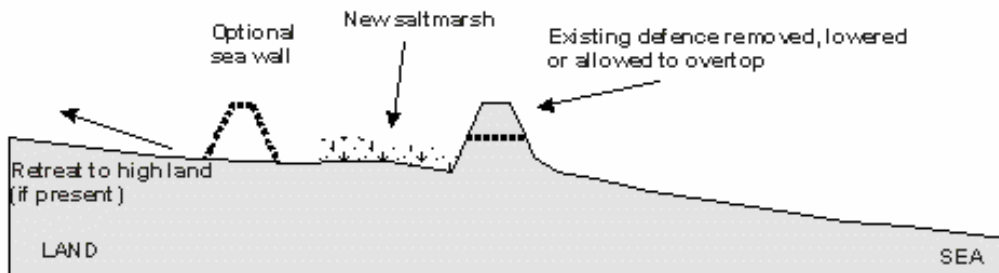


Figure 4.6: Principle of Managed Realignment [Costin, 2004]



Figure 4.7: One of the breaches in Orplands Sea Wall [Costin, 2004]

A distinction is made in 'breach managed realignment' (strategically determined breaches) and 'bank managed realignment' (complete removal of defence). The aim is to create additional saltmarsh and/or mudflat areas.

The principle of foreshore recharge involves the placement of sediments (sands, gravels, muds) to strengthen or rehabilitate the foreshore of tidal inlets, near sea walls, near islands, etcetera. A scheme that has already been carried out is the foreshore recharge scheme at the Hamford Water estuary, acting as a protection of Horsey Island. Another example is the saltmarsh protection at the Pewet Island in the Blackwater estuary. Foreshore recharge is similar to the sand suppletion that is being done along the Dutch coast to maintain the present coast line, however its focus is put more on the promotion of saltmarshes and mudflats.

Another type of schemes in the UK are the Regulated Tidal Exchange (RTE) schemes. The principle of it is already shown in Figure 4.3. The advantage of RTE is that the primary defence remains intact and that, at the same time, new wet habitat is created, e.g. meeting compensatory habitat guidelines near areas where it is being lost.

4.3.2 Preliminary studies for the ComCoast concept (MSc theses)

Coastal flood management in the Netherlands is a matter of vital importance, as the major part of the Netherlands is below mean sea level. Therefore it is a legal obligation to carry out a safety assessment along the lines of a Directive on Safety Assessment of Primary Flood Defences every five years. The standard levels of safety are prescribed in the same law.

In the coastal defence zone a number of 'prioritized weak spots' have been identified, which will be strengthened at short notice, together with an extensive strengthening of the revetments of the sea embankments at many places. The latter is partly caused by sea level rise, as well as by improved understanding of the design wave climate. Recently it became obvious that larger waves may occur than ever anticipated before, being very detrimental for the revetments. A major challenge is to combine the strengthening of the 'weak spots' with the ComCoast concept wherever possible.

The ComCoast concept runs parallel with the current strategy for the Dutch rivers to break with the practice of ever raising the embankments due to increasing discharges. The strategy now is to give more 'Room for the River'. At present, framework plans for the Rhine branches are being formulated and subjected to an EIA (Environmental Impact Assessment procedure). The rehabilitation activities within the Room for the River project will have to be completed by 2015. This strategy also implies a very restrictive policy for construction works in the flood plains of the Dutch rivers, including the Meuse river.

The thesis of Van Pijkeren [2001] deals with an inventory of foreshore and hinterland areas along the Eastern and Western Scheldt estuaries, suitable for the ComCoast concept. In addition, a selection of locations have been made, based on wave overtopping computations. A major conclusion was that the wave overtopping remains within critical limits for hinterland storage when the sea level would rise by 0.85 m. In addition, the loading at the crest and inner slopes would remain relatively moderate: the present standard of 1l/s/m will increase by a factor 10, but this is assumed to be still within the critical condition for good grass cover on a heavy clay layer.

The thesis of Bakker [2003] is a further elaboration of Van Pijkeren's thesis. The thesis confirms the technical feasibility of the wide defence zone concept. In addition, the economic feasibility of the ComCoast concept is analysed. It is concluded that the economy is even probably better than for traditional sea defence strengthening methods (increasing the crest height and volume of the defence).

4.3.3 Retention basins in the Belgian Scheldt estuary

Figure 4.8 shows a 'controlled inundation area' (GOG) in Belgium near Kruikeke-Bazel-Rupelmonde. The inundation area is situated at the left bank of the Scheldt River, not far from Antwerp. The primary goal of this storage basin is to reduce the water levels along the Scheldt. The area is some 5.8 km². In the blue part of the storage area tidal movement is created with a reduced amplitude by inlet- and outlet structures. Together with other storage areas, this project contributes to a major reduction of flood water levels at the Scheldt River near Antwerp.

Projects like this scheme are interesting for the technical aspects (overflow of the embankments), as well as for the societal, legal and administrative aspects. For WP3, the technical information on overflow is an interesting item, as regards the strength behaviour of the embankments during the overflow situation.

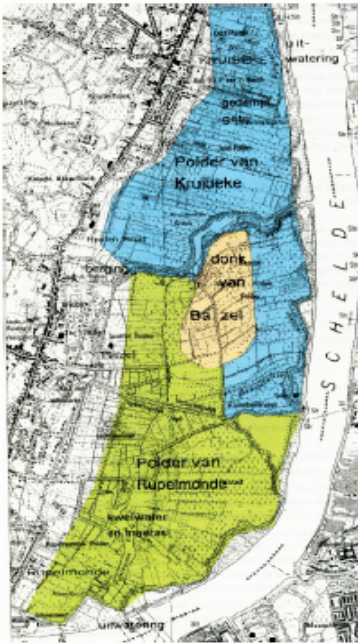


Figure 4.8: Retention basin along the Scheldt river with a Regulated Tidal Exchange area (blue)

4.4 Preliminary evaluation

Based on the foregoing, a preliminary evaluation can be made of various categories of solutions that are related to the ComCoast concept, as shown in Table 4.1.

Five categories of measures are being discerned:

1. Foreshore recharge
This category of measures usually serve foreshore rehabilitation, such as: wetland rehabilitation and improvement, mudflat restoration, promotion of shallow foreshores. As a consequence of these recharge schemes, wave and tidal attack at defences may be mitigated.
2. Measures at outer slope /crest of defence to reduce wave overtopping
Measures to reduce wave attack and overtopping can be applied at the actual defence as well, e.g. by a high seaward berm (wave reduction prior to impact), by applying wave run-up reducing devices (rough elements at the seaward slope and crest) or wave deflection walls.
3. Strengthening of primary defence (not including the hinterland area)
This type of measures for the defence is the basic idea of ComCoast. They concentrate at the crest and inner slope, and possibly at other endangered areas (e.g. to prevent micro-instability). In this category the strengthening of the defences is not linked with a multi-functional hinterland area.
4. Strengthening of primary defence (including the hinterland area)
This compares to 3, however a multi-functional hinterland area is included.
5. Managed realignment schemes
Managed realignment is a step further than 4, i.e. the primary defence system is (partly or fully) removed as to allow tidal movement into the hinterland. Hence, the primary defence function must be taken over, e.g. by upgrading the secondary defence or by a sloping terrain (the latter can commonly be observed in the UK).

It should be remarked here that Regulated Tidal Exchange is a type of ComCoast application that fits well in system 4.

The feasibility is rated by scoring the category at several aspects, based on sound engineering judgement. These aspects are: hydraulic effects, coastal related or not, technical status, environmental impact, societal acceptance, legal/administrative feasibility and physical adequacy.

The score + indicates a positive feasibility with the aspect. The score 0 indicates an intermediate or neutral feasibility, whereas a score – is a poor feasibility. Combinations indicate a band with of effects. The fat score on top is the overall score per category of measures.

It should be kept in mind, that for this preliminary rating the various solutions cannot directly be compared, as their exact goals may be different. Rather, it gives an impression on the feasibility of the various solutions in itself. All solutions are considered to be feasible on average, except for some doubts on

strengthening of the primary defences without introducing a wide wetland zone. The latter condition may also comprise Regulated Tidal Exchange, as this may highly promote the public and political acceptance.

Table 4.1: Preliminary rating of feasibility for the ComCoast principles

Category of measures	Relevant aspects	Feasibility for ComCoast + 0 and -	Remarks
1. Foreshore recharge (combination with primary defence)	<ul style="list-style-type: none"> hydraulic effects coastal related? technical status environmental impact societal acceptance legal / administrative feasibility physical adequacy 	<p>+</p> <p>+</p> <p>+</p> <p>+</p> <p>+</p> <p>+</p> <p>+</p> <p>+/0</p>	<p>overall score</p> <p>reduction tidal/wave action</p> <p>coastal/estuarine environment proven; reduction of loads on defences</p> <p>preservation of wetland area</p> <p>defence system not adapted</p> <p>no direct interaction, compensation of wet habitat area</p> <p>combination with other measures?</p>
2. Reduction of wave overtopping by adaptation of primary defence	<ul style="list-style-type: none"> hydraulic effects coastal related? technical status environmental impact societal acceptance legal / administrative feasibility physical adequacy 	<p>+</p> <p>+</p> <p>+</p> <p>+/0</p> <p>0</p> <p>+</p> <p>0</p> <p>+/0</p>	<p>overall score</p> <p>local reduction of wave overtopping</p> <p>coastal/estuarine environment partly proven; partly innovative</p> <p>no significant effect</p> <p>no major change of defence</p> <p>possibly neutral</p> <p>combination with other measures?</p>
3. Strengthening of defence (line system)	<ul style="list-style-type: none"> hydraulic effects coastal related? technical status environmental impact societal acceptance legal / administrative feasibility physical adequacy 	<p>0/+</p> <p>+</p> <p>+</p> <p>+/0</p> <p>0</p> <p>-/0</p> <p>0</p> <p>0/+</p>	<p>overall score</p> <p>reinforcement of crest and inner slope</p> <p>coastal/estuarine environment partly new technology</p> <p>less natural appearance etcetera</p> <p>psychological turnaround ref. overtopping</p> <p>change in wave overtopping standards may be feasibly</p> <p>possibly sufficient</p>
4. Strengthening of defence (wide system)	<ul style="list-style-type: none"> hydraulic effects coastal related? technical status environmental impact societal acceptance legal / administrative feasibility physical adequacy 	<p>+</p> <p>+</p> <p>+</p> <p>+/0</p> <p>+</p> <p>+</p> <p>0</p> <p>+</p>	<p>overall score</p> <p>reinforcement of crest and inner slope</p> <p>coastal/estuarine environment partly new technology</p> <p>wetland area landward side acts positive</p> <p>wide zone has better acceptance</p> <p>change in wave overtopping standards, new standards secondary embankments</p> <p>sufficient</p>
5. Managed realignment	<ul style="list-style-type: none"> hydraulic effects coastal related? technical status environmental impact societal acceptance legal / administrative feasibility physical adequacy 	<p>+</p> <p>+/0</p> <p>+</p> <p>+</p> <p>+</p> <p>+/0</p> <p>+/0</p> <p>+</p>	<p>overall score</p> <p>reduced tidal/wave action sec. defence</p> <p>estuarine environment</p> <p>successful schemes are realized</p> <p>saltmars/mudflat area increase</p> <p>high valued wetlands vs abandoning land</p> <p>new standards secondary embankments, compensation of wet habitat area</p> <p>sufficient</p>

5. REVIEW OF CONCEPTS FOR REINFORCEMENT OF THE SEA DEFENCES

5.1 Approach

The focus of technical concepts relevant for the ComCoast concept, is on the reinforcement of the crest and inner slope of the sea defences. The reason for this is that these zones will experience the strongest increase in loads (wave overtopping) and, in many cases will have to be strengthened to cope with this increase. The present chapter deals with a brief review of reinforcement concepts of the crest and inner slope.

An important item is reduction of wave overtopping, e.g. by foreshore adaptation, increase of roughness of the outer slopes to reduce wave run-up etcetera. Relevant references have been identified, but in the present chapter this type of measures are not considered, as the focus is on improving the strength (at crest and inner slope) and not at reducing the loads.

The outer (sea-ward) slope will also experience some increase in loads, but this is relatively less than on the inner slopes. In addition, the outer slopes are usually already heavily reinforced, e.g. by the presence of stone pitching; increase in storm surge levels on the outer slope may result in a higher desired level of stone pitching. The latter is left out of consideration in this inventory, but should be addressed in an integrated design of sea defences that can cope with more extreme loads (higher and longer waves and higher water levels). It is remarked here that for stone, concrete and asphalt revetments at the outer slope, a lot of knowledge has been developed. This is obvious, as this outer slope stability has been the main issue in sea defences up to now. This knowledge is a major reference for the crest and inner slope when very severe overtopping would be allowed. However, it can be doubted if such an overtopping will be practical. Allowance of moderate overtopping and avoidance of full wave impact on the crest and inner slope seems to be more realistic for the time being. Hence, crest and inner slope reinforcement shall usually be much less heavy than the (existing) outer slope reinforcement.

After a brief review of potential failure mechanisms for sea defences, existing systems for reinforcement of defences are presented. From these systems, a selection of potentially the most feasible systems is presented. Details on these systems are shown in the 'fact sheets' in appendix A.

5.2 Failure mechanisms

This review of failure mechanisms focuses on the stability of the inner slope of sea defences.

Major failure mechanisms of the inner slope are:

1. *External erosion of the protection material at the inner slope (inclusive of grass revetments)*

This is relevant when the water level exceeds the crest level (in case of absence of waves) and/or when increased waves overtop the defence structure. This is schematically shown in the sketch below.

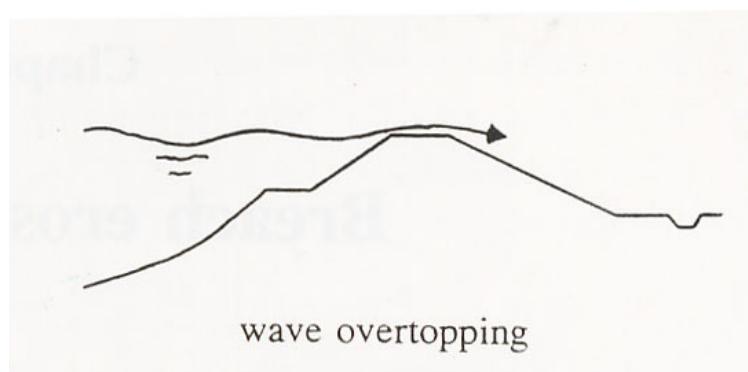


Figure 5.1: Sketch of the mechanism: 'mechanical erosion of the inner slope by wave overtopping'

2. Micro instability

This is the erosion of the inner slope material as a result of ground water seepage at the inner slope after long-duration flood waters.

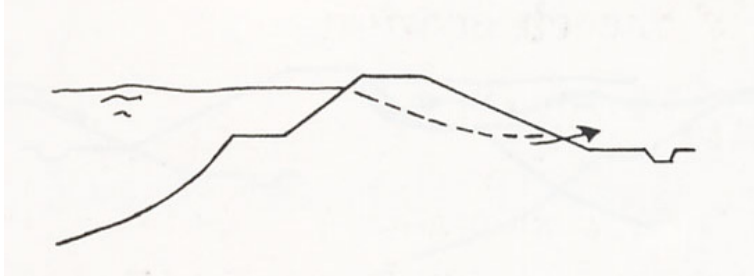


Figure 5.2: Sketch of the mechanism: 'micro-instability'

3. Inner slope macro instability

Inner slope macro instability is sliding of a part of the inner slope along a deep slip circle. This may occur during flood waters by an increase of the water pressure and an decrease of the shear resistance in the slip circle, as indicated in the sketch below.

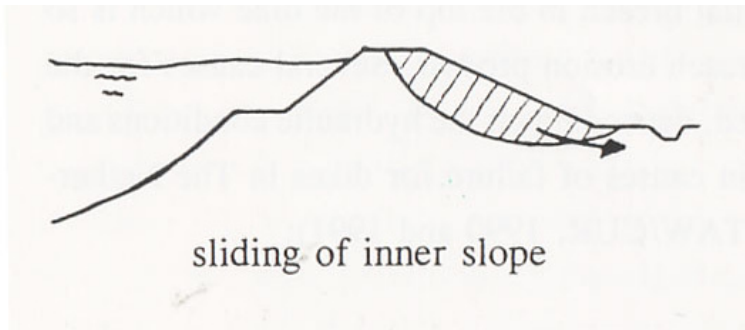


Figure 5.3: Sketch of the mechanism: 'inner slope macro instability'

Apart from the aforementioned failure mechanisms some indirect mechanism may also influence the stability of the inner slope. These are reviewed hereafter.

4. Piping

This phenomenon is the erosion underneath the embankment along a subsoil interface between a porous layer and a non-porous layer. As a result a branch like system of 'pipes' may occur. This may finally result in undermining of the embankment body and ultimately in collapse of the embankment. In addition, the adjoining hinterland may experience well formation. Such a well is a major introducing mechanism for piping, as erosion will propagate strongly from such a well towards the upstream side, as shown in the sketch below.

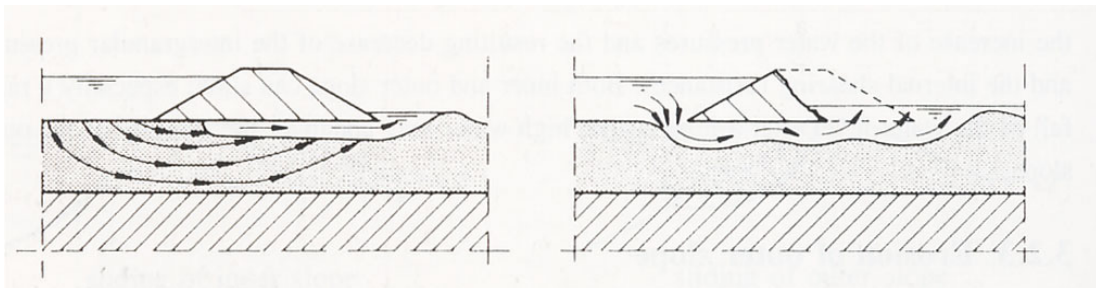


Figure 5.4: Sketch of the mechanism: 'piping' by retrogressive erosion of a well underneath the embankment body

5. Uplifting of the hinterland

This phenomena can sometimes be observed after a long period of flood stages, in combination with a soft non-porous layer(s) on top of a porous (e.g. sandy) layer. The water pressures in the pores of the porous layer may increase to a level that the soft top layer(s) are being lifted and the top layer(s) begin(s) to float. In this situation the horizontal shear forces of the embankment may not be transferred properly towards the subsoil. Hence this may lead to inner slope macro instability. The situation of uplift is shown in the sketch below.

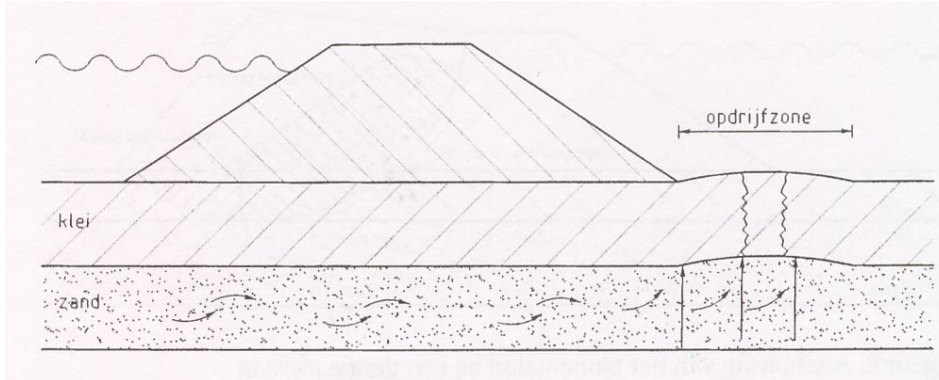


Figure 5.5: Sketch of the mechanism: uplift of the hinterland

When looking to the new loading conditions, relevant for the ComCoast concept, mechanical surface erosion of the inner slope (and the crest) is the foremost failure mechanism. In addition, also the phenomenon of inner slope macro instability may be important. These failure mechanisms are the most critical for initial damage. The major increase of these latter failure mechanisms for ComCoast is partly due to the increased water levels at the outer slope. The biggest contribution, however, is likely to come from increased softening of the inner slope by increased amounts of overtopping water and longer duration of the situation that this overtopping occurs. The other failure mechanisms do require longer durations of flood waters, which is not a likely situation in coastal conditions (instead, these phenomena are highly relevant for river embankments). In addition, sea defences are usually more 'heavy' (faint outer and inner slopes) than river defences, reducing the danger of piping and uplifting.

Hence, surface erosion of the inner slope and inner slope macro instability are considered as the major initial failure mechanisms for ComCoast. The latter mechanism is the domain of soil mechanical stability and is addressed only sideways in this report.

The fault tree of subsequent damage at the inner slope, due to (increased) overtopping, is shown in the figure below. From figure 5.6 it can be seen that, apart from ongoing surface erosion, failure can also be triggered by the occurrence of cracks. After a crack, saturation of the inner slope will be intensified, after which part of the slope can slide off (shallow or deep slip). Hence, in case of unprotected slopes initial damage to the surface (erosion, cracks) different subsequent failure mechanisms can occur.

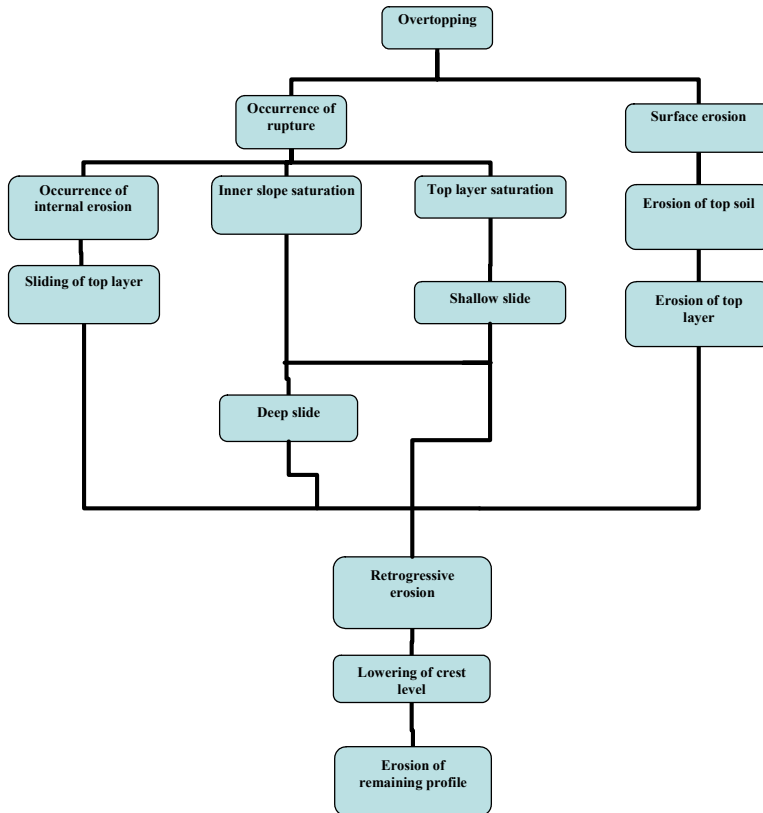


Figure 5.6: Flow diagram of the failure of an embankment dam by overtopping

This is also shown in figures 5.7 and 5.8. These phenomena are related to increased overtopping as indicated below (the water level upstream is illustrative here, as no wave action is shown):

1. Occasional overtopping over the embankment crest; there is no continuous flow of water over the inner slope
2. Regular overtopping: the amount of water is that high that it may infiltrate in the embankment body
- 3.A Surface erosion (figure 5.7)
 - Erosion of grass sod
 - Erosion of topsoil and subsoil layers

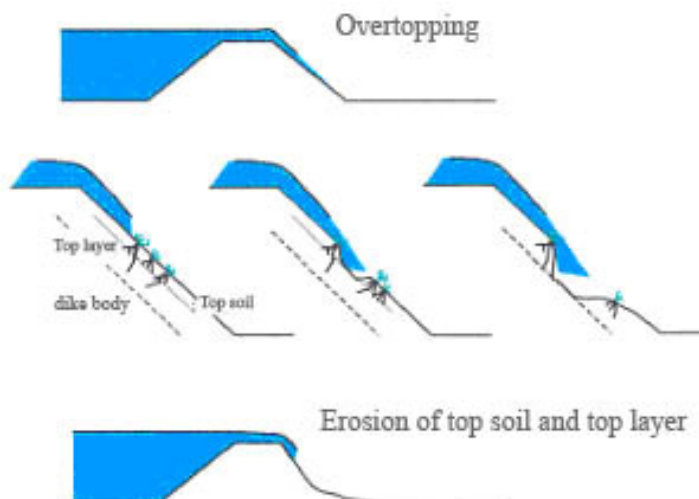


Figure 5.7: Surface erosion by wave overtopping

3.B Longitudinal cracks (Figure 5.8)

- Internal erosion by infiltrating water that progresses towards lower parts of the slope and pours out locally; this may lead to 'tunnel erosion'
- Saturation of the inner slope and ongoing sliding of parts of the slope
- Increase of water pressures underneath the top layer or under layer and deep slip failure

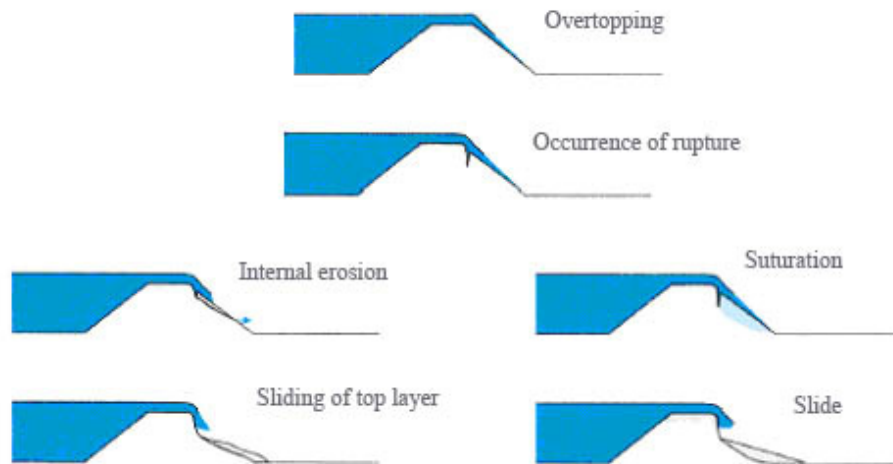


Figure 5.8: Internal erosion and sliding of parts of the inner slope

5.3 Review of existing systems to strengthen the crest and inner slope

In the review of the efficacy of reinforcement systems the aim is to prevent initial failure, as regards the tremendous importance of the function of primary sea defences. Yet, consideration of subsequent failure mechanisms is important as to assess the self-healing properties of reinforcement systems in the case that unexpected initial failure would occur.

Reference situation

A grass revetment on top a clay layer is the reference revetment for the crest and inner slope of embankment type sea defences in countries around the North Sea. A grass cover is able to withstand light to moderate overtopping, dependent on the duration.. The erosion resistance of grass is promoted by its root system, which is performing like a natural anchoring system of the grass. At the same time the roots do prevent the clay sods to erode, so the clay layer is anchored as well and the grass blades cover the surface of the clay, hence preventing surface erosion of the clay.

Obviously, for good erosion resistance, the grass cover should be in good condition and the root system should be well-developed. Hence, good maintenance is important; e.g. grazing by sheep and prevention of bare spots by cattle tracks, near obstructions, and so forth. Due to meteorological variations, the condition of the grass cover will be varying as well.

For short-duration impacts that are not extremely big, a grass cover is an excellent system to prevent erosion against overtopping, against wind and against human and animal access. For longer duration impacts, the (over)saturation of the clay layer is counteracting the erosion resistance and clay sods may gradually be removed from the impact area. This is a slow process, but in the end it may lead to failure of the complete cover and subsequent intensified erosion of the crest and inner slope.

The increasing loads and durations to be encountered within the ComCoast concept, imply that from a certain level of overtopping impact, reinforcement of the crest and inner slope are unavoidable. At present, criteria for overtopping are generally considered as conservative. Hence a further reconnaissance of the (ultimate) erosion resistance of grass revetments should be pursued. The state-of-the-art of grass revetments is still showing knowledge gaps that need further research.

Reinforcement systems

Hereafter, a review is presented of potential materials that can be used to reinforce the crest and inner slopes of sea defences (earthen embankments).

1. Reinforced grass systems. By applying supporting materials in the grass cover and underlying clay layer, the erosion resistance can be boosted. Two main systems for reinforcement can be discerned: supporting open geotextile systems and open concrete systems that allow for vegetation growth. Both

- systems support the subsoil from erosion and promote the hold of the grass cover onto the subsoil. For moderate ComCoast conditions the supporting geotextile systems do seem to be very promising (e.g. 'structure mats'). Concrete systems are more costly and may cope with more severe overtopping.
2. Gabions. Gabions are wire mesh boxes containing rockfill stones or rubble. The wire mesh can be made of steel wire or synthetic wire. They can be placed into the top of the crest and inner slope in the form of flat boxes ('gabion mattress') and they show a good stability against severe overtopping of waves.
 3. Concrete block mattress systems. These systems consist of interlocked concrete paving elements or concrete blocks. Interlocking is obtained by connecting geotextiles, pins or cables. The mattresses are mounted at a placement frame. These block mattresses are also available as open system (mentioned at 1) as to allow for vegetation growth in the voids. The latter type seems to be the most desirable for ComCoast applications.
 4. Rockfill protection systems. For severe impacts rockfill protection systems may be applied, comparable to the application of rockfill spillway chutes. In addition, rockfill protections are widely used in flow regulation structures, bed and bank protections at slopes that that directly attacked by flow and/or waves
 5. Pitched revetments. Pitched revetments are tightly placed loose elements, e.g. concrete tiles, blocks, natural basalt, granite or limestone pillars. Like the rockfill protection systems, pitched revetments are placed on suitable sub layers preventing washing out of subsoil undermining of the revetments. In order to further increase the erosion resistance, these revetments can be 'glued' by filling the voids with colloidal mortar or (pouring) asphalt. .
 6. Geotextile sand-filled elements (massive). Different types exist: geobags, geotubes, geomattresses and geocontainers. For application on embankment slopes, geomattresses may be considered. (geobags are only used as a back-up system in case of emergency damage repairs).
 7. Open asphaltic systems. A suitable type is the 'open' stone asphalt, that allows for settlement of light vegetation.
 8. Impervious asphaltic systems. For embankment protection, the asphaltic systems have the disadvantage to be highly of fully impervious. Hence, the thickness should be large enough to withstand water over pressures underneath the slab. At the other hand, the asphalt system should also be able to adjust to settlements of the embankment. If these conditions are met, asphaltic systems are able to withstand extremely high impacts.
 9. Concrete systems. These systems are fully impervious and they obtain their stability from the dead weight. Weak points are the joints in between the concrete plates. Like asphaltic systems, they are able to cope with extremely high impacts. However, opposed to asphaltic systems that may still have some flexibility by creep, concrete slabs don not have any flexibility at all and therefore are not recommended on the inner slope of earthen embankments.

5.4 Preliminary evaluation of existing reinforcement measures

In this section a preliminary evaluation is given on the feasibility of the systems mentioned in Section 5.3, as an illustration of the evaluation methodology. This evaluation is limited to the resistance against wave overtopping: other failure modes are not considered here.

The evaluation is done for different criteria with a score -1 (less favorable), 0 (neutral) and 1 (favourable). As the criteria are not all of the same importance, a weight factor (1-3) is attributed to each criterion, with which the score is multiplied as to arrive at an overall evaluation. When the end score figure is positive the system is potentially feasible. To get a more elaborated answer on the feasibility of each system, an in-depth study is required, which is outside of the scope of the present inventory.

The previously indicated systems to be judged are briefly indicated hereafter:

- reinforced grass
- gabions
- open concrete mattresses
- rockfill
- pitched revetments
- geotextile mattresses
- open asphaltic systems
- impervious asphaltic systems
- concrete

As an illustration of the selection method, in the table below (arbitrary) weight factors for the various criteria are shown.

A separate item, that should be considered, is the adaptability for coping with further increasing impacts, indicated as 'adaptation'. For instance, systems that can cope with extreme loads, have a high adaptation,

in case of a future increase of loads by ongoing sea level rise. However, when this increase is anticipated to thus small that the overtopping remains limited, a more 'modest' reinforcement may suffice. Hence this property is not given a weight factor, but is should be taken into account separately. The adaptation to increased loads is setting a selection criterion on beforehand ('boundary condition') for a reinforcement system.

Table 5.1: (Arbitrary) Weight factor for different criteria for reinforcement of the inner slopes of earthen embankments sea defences

adaptation ref. increased loads	weight
	n.a.
nature potentials	3
environmental impact	1
maintainability	3
proven technology	1
recreational potential	2
sensitivity to vandalism	1
sustainability (lifetime)	2
scenic quality	2
animal accessibility	2
cost	3

The weight of nature potentials, maintenance and costs are considered to be the most important. The environmental impact is considered to be a minor item (this impact is hardly identifiable), as well as proven technology (new systems can easily be tested) and vandalism (to be counteracted by monitoring).

In table 5.2.the indicative scores of the different reinforcement measures are indicated.

Table 5.2: An example of the results of the multi criteria analysis for different reinforcement systems based on arbitrary weight factors of table 5.1

	weight	reinf grass	gabions	concr matr	rockfill	pitching	geomatrr	open asphalt	imp. asphalt	concrete
adaptation ref. increased loads	n.a.				0	+	0	+	+	+
nature potentials	3	1	0	1	0	-1	1	0	-1	-1
environmental impact	1	0	0	0	0	0	0	0	-1	0
maintainability	3	1	-1	0	0	1	0	1	1	1
proven technology	1	-1	0	1	1	1	-1	1	1	-1
recreational potential	2	1	-1	0	-1	0	1	0	0	0
sensitivity to vandalism	1	1	-1	1	0	1	-1	1	1	1
sustainability (lifetime)	2	0	0	0	1	1	-1	1	1	1
scenic quality	2	1	-1	0	0	0	1	0	-1	-1
animal accessibility	2	1	-1	0	-1	0	1	0	0	0
cost	3	1	-1	-1	0	-1	0	0	0	-1
TOTAL SCORE:		15	-13	2	-1	1	5	7	1	-3

From this illustrative (preliminary) evaluation it can be concluded that reinforced grass is a potentially highly feasible system. Gabions have a low score due to several negative aspects. The scores of the other systems are intermediate.

The conclusion above may be reversed when dealing with high overtopping impacts ('adaptation'). In this case (open) asphaltic systems and ('open') concrete mattresses may be required in case of severe overtopping. In case of moderate overtopping, geotextile mattresses as well as rockfill and pitching may be used. When relatively light overtopping applies (this can be order of magnitude larger than the present condition) reinforced grass revetments are possibly applicable. A note should be made here at this point. Due to the very intermittent character of wave overtopping and the rather good resistance of a (reinforced) grass cover in that situation, the resistance of reinforced grass revetments may practically lay within the limits of overtopping that are foreseen within ComCoast. Further elaboration in the next stage of WP3 may give a definite answer to this assumption.

As remarked earlier, the systems considered here are rather well-known systems. However, we think that even within these systems, important *innovative improvements* can be developed by small adaptations of these systems. The reason for this is that the application at the inner slope and crest of sea defences means a new functionality that is different from applications up to now and hence, optimum design may be different from current practice. Other innovations may be found as well outside of the systems presented here.

More details of these selected reinforcement systems can be found in the Fact Sheets attached to this report, which have been elaborated within the framework of this study. In the cost indication of the different systems, it is assumed that a system is applied at a large scale. Price level is commonly the year 2000, unless specified otherwise.

5.5 Remark on soil-mechanical reinforcements

Soil mechanical reinforcements may be useful as well for strengthening embankments within ComCoast. This need to be studied further. As an introduction hereafter some current innovative geotechnical strengthening methods are presented. These methods focus on improvements on macro-stability behavior.

INSIDE (INnovations on Stability Improvements enabling Dike Elevations)

The INSIDE research programme has been set-up by the Dutch Ministry of Public Works and Transport and aims at developing new techniques for geotechnical reinforcement of embankment dams (dykes). The rationale of this is to obtain dyke reinforcements without the necessity of 'blowing up' the volume of the dyke, as to avoid to remove buildings that have been built against the dykes.

The new techniques focus on reducing the risk of macro instability of the inner slope of the embankments. This failure mechanism is more apparent for river dykes than for sea defences. However, the risk of macro instability cannot be excluded in coastal areas, especially not when sea water levels rise and overtopping will increase.

Up to now three new techniques have been developed:

- **Mixed-in-Place:** this method involves the in-situ construction of reinforced soil columns. These columns are obtained by mixing soil with a binding agent. The mixing device uses an air pressurized dosing method that is 'mixed in place'. This technique can be applied successfully in weak soils, e.g. to prevent the mechanism of lifting of the adjoining hinterland strip along the embankments and to stabilize the inner slope against the direct danger of macro instability.
- **Dyke Nailing:** This technique implies the application of pulling nails that function as anchors. The nails are wrapped with a concrete grouting mass. By this technique a large shear stresses can be mobilized within the embankment, thus giving more resistance against macro instability of the inner slope.
- **Expanding Columns:** the concept of this method is to construct a tube with an expandable mantle wrapped around it, oblique through weak subsoil layers into the sandy, well-bearing, layer. After placement of the tube, the mantle is expanded with cement-bentonite. The Expanding Columns act as dowels through the potential slip circles. This method is illustrated in the figure below.

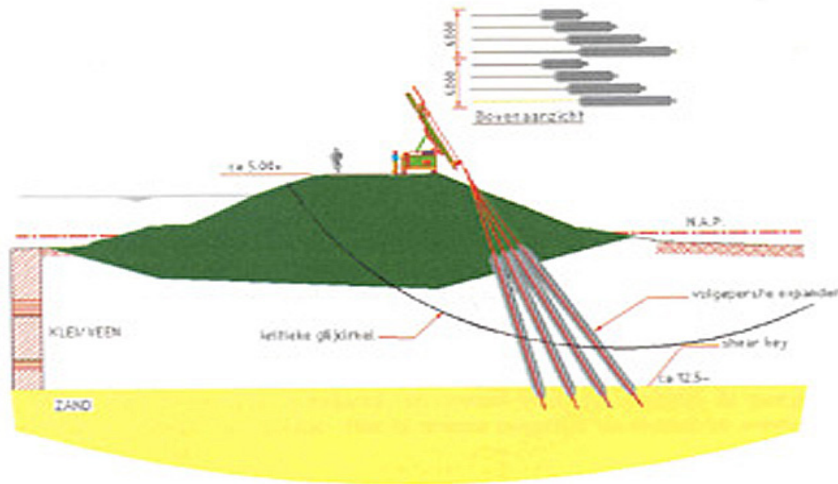


Figure 5.8: INSIDE technique for improvement of geotechnical stability

Other soil mechanical issues

A major issue is the prevention of weak spots in interfaces between layers with different permeability, as these interfaces may potentially bring about dangerous failure mechanisms (e.g. piping, sliding off). In addition, the water table fluctuations within the embankment body and the control of undesirable levels, is also a major point of interest.

Reducing the water table in the embankment can be favored by e.g. applying a drainage system. This system however may not lead to increased fluctuations (contradictory requirements).

The development of Innovative designs as mentioned in Section 5.4 should preferably also improve the soil mechanical behavior where possible.

6. CONCLUSIONS AND RECOMMENDATIONS

Some major conclusions are:

- The systematic retrieval of relevant items for ComCoast provided about 160 items thus far. Additional items can emerge during the subsequent phases of WP3, augmenting the benefit of the database. Also other Work Packages within the ComCoast project might benefit from the database.
- Most items relate to technical aspects of ComCoast (on which the focus was laid in this inventory).
- The ComCoast concept may be elaborated further along different types of measures and combination of measures may be useful. Illustrative examples have been presented in this report.
- The technical state-of-the-art indicates a need for additional targeted research and new innovative solutions.
- Improvements of the reinforcement of the crest and inner slope surface stability should preferably be combined with improvements of the geotechnical behaviour.

It is recommended to update the database continuously with newly traced information during the next study phases of ComCoast, with special reference to the partner contributions and contributions of other Work Packages.

The feasibility of reinforcement methods should not only address the resistance against the direct impact of overtopped waves (external erosion resistance), but also the other failure mechanisms that may apply (or even become more critical). This is highly relevant, as regards the more severe overtopping, higher sea water levels and ongoing subsidence. Hence, the development of an *overall judgement framework* is highly recommended, prior to further elaboration of reinforcement systems in the next phase of WP3.

A third recommendation is to promote *innovative* concepts and solutions for ComCoast in the next research phases of WP3.

APPENDIX A: FACT SHEETS

FACT SHEET 1: Reinforced grass revetment; open geotextile structure

Application

By applying materials that reinforce the grassed topsoil, the erosion resistance during wave overtopping can be increased considerably. This allows to satisfy more severe design requirements, while maintaining economical and environmental advantages of the grass vegetation revetments.



Figure FS1.1: Cross section of a reinforced grass revetment

The erosion resistance against surface erosion, as well as internal erosion, can be promoted by applying geotextile nets or open mattresses. The open structure of the geotextile should allow for unhampered growth of vegetation roots. The coherence of the topsoil that is obtained by the entanglement of the roots and geotextile results in an improved resistance against erosion. Optionally, pins can be applied as well as to prevent shallow slip circle development.

Constructional aspects

- As to promote the development of a good root system after installation of the geotextile mattress, the following operating procedure is suggested: light 'over-filling' of the geotextile with garden mould and subsequent seeding.
- The geotextile may have some influence on the amount of water that can penetrate into the subsoil (this, however, will be strongly dependent on the geotextile system that is used). Hence, a toe drainage facility may be required to release water pressures at the inner slope area. This is dependent on the geometry and composition of the earthen defence and the boundary conditions. A strong increase in overtopping discharge will generally lead to the necessity of a toe drainage facility.
- The resistance against surface erosion and against shallow slip, can be safeguarded by a good anchoring of the grass revetment and a strong entanglement of the reinforced system as a whole. A deep root system offers the best resistance against sliding forces and uplift by water overpressures. Anchors and /or pins may further promote the anchoring.
- Experiments showed that extremely high flow velocities can be allowed, up to about 5 m/s, under short exposure times. This is possible without showing any damage, according to data of the Enka Company.
- The open geotextile mattresses have a very high life time expectancy.
- After seeding, the grass root growth can be promoted by the following measures (e.g. important during the low temperature season or drought periods during summer):
 - Application of chemicals that give improved binding of the subsoil, by which the water can better be hold into the subsoil.
 - Hydro-seeding: irrigating the slope with a mixture of seed, binding agent, vegetation nutrients, stabiliser and water.
 - The application of biologically decomposable geotextiles. As an example: mattresses of straw and coconut fibre decay after some time by composting and, consequently, may only serve as a temporary measure.

Operational aspects

Geotextiles protruding above the surface, are susceptible for damage by animals, mowers and vandalism, and hence, need regular inspection. Hence, this should be avoided. When not damaged, protruding geotextile materials may be attached again to the subsoil (pins) and may be covered again with garden mould and seeded again. When damaged, extensive repairs may be necessary (overlapping the damaged areas with new geotextiles).

Environmental aspects

The free development of vegetation is excellent for this type of reinforcement measures. After growth of the grass vegetation, the geotextile will be fully integrated in the grass revetment and the geotextile reinforcement will be invisible. Hence, the landscape impacts are nil, as compared to a non-reinforced grass vegetation.

Examples

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.

Available knowledge / knowledge gaps

Formal knowledge and experience of the erosion and stability promoting effect of reinforced grass revetments is insufficient. Hence, such an improvement is not being taken into account formally in the Netherlands. Nevertheless, the test results and scarce experiences show that major improvement can be expected. Therefore, further in-depth research on different types of reinforcement systems seems to be very useful. As a basis to this, relevant information can be found in:

- CIRIA; Design of reinforced grass waterways, 1987.
- Philips; Design of stream bank stabilization with geogrid reinforced earth systems, 2000.
- M. Klein Breteler, WL| Delft Hydraulics; Grass revetments: supplementary analysis of the water movement at the inner slope, 1996 (in Dutch).

Cost indication

De construction costs for a reinforced grass revetment are composed out of the following components (order of magnitude):

- | | |
|--|-------------------------|
| • removal and disposing of the existing revetment | € 5,- / m ² |
| • levelling of the surface / installation of the geotextile mattress | € 10,- / m ² |
| • filling up with garden mould | € 1,- / m ² |
| • seeding with grass | € 0,5 / m ² |

FACTSHEET 2: Gabions (filled wire mesh cages)

Application

A gabion is a wire mesh cage filled with stones or other materials. The (steel) wire can be protected against corrosion by galvanizing or plastic coatings. It may be an attractive solution at places that don't need to be tread on and is increasingly being applied at steep bank slopes. Gabions have a good erosion resistance against flow and wave attack. For the inner slope and crest of embankments, mattresses seems the most logical type for applying gabions. The thickness of the gabion mattress is depending on the amount of wash-over.



Figure FS2.1: 'Stepped' gabion in urban river bank



Figure FS2.2: Gabion mattress on a slope of a future river bank

Constructional aspects

- Compared to loosely placed stones, the same stone sizes applied in a gabion will result in a much greater stability and therefore less material is needed.
- The gabions are preferably PVC-coated when used in a marine environment, as to prolong the life-time.
- It should be checked that the gabions are filled to the maximum level to prevent settlement and internal migration within the gabion;
- The permeability of gabions is high, reducing excessive uplift pressures.
- Gabions are usually manufactured and filled at the worksite. This can be done with simple means (hand-labour).
- The filter requirements with the subsoil need to be checked and usually a filter cloth of granular filter layer needs to be applied.

Operational aspects

The durability is determined by the lifetime of the wire mesh, i.e. the use of plastics or type of steel and the environment in which the gabions are placed. Steel is affected by corrosion and the pH-value of its surroundings. On the long-term the plastic coating is sensitive to the exposure of sun light and frost. A construction of gabions does not require substantial maintenance and, if needed, it can be carried out easily. In case of frequent and severe overtopping it should be checked if material underneath are washed-out.

Environmental aspects

The flexible application of (local) aggregate materials to fill the cages, is a sustainable aspect of gabions, compared to e.g. the application of large rockfill when this needs to be hauled over large distances to the construction site.

Just after placement the wire mesh cages will be clearly visible. When filled with garden mould, however, vegetation may develop very well, see Figures FS 2.3 and 2.4, providing a nature friendly solution of bank protection. It provides a habitat for small plants and animals. Nevertheless, (bare) wire mesh is rather sharp and animals may be caught. In The Netherlands, dykes also have an agricultural function; grazing grounds for sheep, that maintain the grass cover. Probably, the application of gabions will not allow for grazing of sheep.

Examples

In the Netherlands gabions have been applied as riverbank protection at several locations. The website of Nautilus Schanskorven B.V. shows a nice example of the ability of gabions to fit perfect in the surroundings.



Figure FS2.3: Gabion riverbank protection
just after construction

Figure FS2.4: The same spot as on the left;
gabions overgrown by plants

Available knowledge and knowledge gaps

Gabions are widely applied as a riverbank lining, hence knowledge and studies regarding this subject are available. The application of gabions at a crest and/or inner slope protection of dykes is not common and additional research seems to be necessary at this point to quantify the stability against overtopping (although it is assumed that this stability will be relatively good). Relevant information can be found in:

- CUR, Report 168a, Bank protection materials, Gouda, 1994 (in Dutch).
- CUR-Publication 202, Environmentally friendly banks; bank protection materials, CUR, Gouda, 1999 (in Dutch).
- CUR-Publication 200, Environmentally friendly banks, approach and applications, CUR, Gouda, 1999 (in Dutch).

Additionally, product information can be found; e.g. from Nautilus Schanskorven b.v. (www.nautilus-bio-civil.com) and Maccaferri (www.maccaferri.com).

Cost indication

Gabions are available in almost any thinkable dimension. The (mattress) installation costs are dependent on the thickness of the gabion and the type of wire mesh. A rough figure of the costs (price indication year 2000) of a gabion is: € 70 / m². For a gabion mattress the costs can be lower, dependent on the thickness e.g. about € 50 / m². Additional costs are for removal of the present protection (e.g. € 5 / m² and up) and levelling of the subsoil.

FACT SHEET 3: Open concrete block mattress systems

Application

A concrete block mattress is a bank protection system of interconnected concrete elements. The elements may have different shapes, tuned at the specific situation that they will be used for. Such a concrete block mattress may have an open character, by providing sufficient spacing in between the elements. De interconnection can be realized by cables, hooks, or a strong geotextile fabric at which the elements are mounted by pins or other means.

Open structure mattresses can be used as bank or bed protections in a wide variety of situations and conditions. They can also successfully be applied in conditions of wave attack, e.g. for direct impact at the outer slope of an embankment or for indirect impact at the crest and inner slope. The open structure mattresses may allow for good conditions for vegetation growth.



Figure FS3.1: installation of an open concrete block mattress

Constructional aspects

A major advantage of the open concrete block mattress is the easy and efficient installation. In addition, the following aspects are mentioned:

- Re-use of open concrete mattresses may be difficult, as the connections may get broken.
- To prevent uplift and sliding off, the upper side of the mattress should be anchored properly. Usually this will not be needed for the toe-part of the mattress.
- The hydraulic stability (against currents and waves) of open concrete mattresses is generally better than more traditional (impervious) revetments. This can be attributed to the relative good permeability (no danger for uplift) at the one hand, and at the interconnection of the elements at the other hand.
- The filter requirements need to be met, e.g. when applying a geotextile fabric or a granular filter.
- Weak points of this mattress system are the edges of the mattress, e.g. the joints in between connecting mattresses. The edges may get unstable, when they cannot be connected in a similar way as the remainder of the mattress. In selecting proper systems, ample attention needs to be paid at this item.

Operational aspects

Repairing concrete block mattresses is cumbersome, as compared to many other systems, as a relative large part of the slope needs to be re-fitted. This is a big disadvantage as compared to e.g. a pitched stone revetment, consisting of loose stones or blocks. This disadvantage can be coped with by proper design and construction, as the maintenance of this type of protection may be practically nil during its lifetime. The lifetime is at least 15 year.

The most critical in the lifespan are the connection elements (cables, pins, strong geotextiles). These connections need to be well-resistant against the action of (sea)water, sunlight, vegetation roots, animals, and so forth. The interconnection offers a good barrier against vandalism.

Environmental aspects

By its open structure, this type of concrete mattresses offer good opportunities for the settlement of vegetation. This is especially true for herbal vegetation. The protection may be sensitive however for

damage by larger shrubs and trees, so this type of vegetation needs to be avoided by proper maintenance. By seeding grass, a rather closed grass vegetation may be obtained, dependent on the system that has been chosen (e.g. additional placement of garden mould).

Examples

As mentioned before, open concrete block mattresses are applicable in a wide variety of circumstances, and so there is an abundance of examples. For many banks of navigation channels open concrete block mattresses are used to cope with the by ships induced waves.

Available knowledge / knowledge gaps

Practical knowledge is widely available. For severe circumstances, e.g. for sea defences, research has been carried out as to provide a good basis for design. A reference is:

- J.P. de Waal e.a.; Alternative open bank protection systems, WL Delft Hydraulics 1998 (in Dutch).

This reference focuses on the stability of the open concrete mattresses under severe wave attack and current attack. Different failure mechanisms have been taken into account: uplift, sliding off, and the soil mechanical interaction.

Cost indication

Concrete mattresses are available in a wide variety. The installation costs are strongly dependent on the thickness of the mattress (elements) and the type of the open structure. Costs may roughly vary in between € 25 to 40 / m². Additional costs are for removal of the present protection (e.g. € 5 / m² and up) and levelling of the subsoil.

FACTSHEET 4: Rockfill protection systems (riprap)

Application

The term rockfill, or riprap, usually applies to armouring stones with a stone size larger than a few centimetres. These stones are generally bulk-placed. In case of a bank protection, riprap will be placed on top of a geotextile to meet the filter requirements and prevent washing out of the subsequent layer. When riprap is placed on the inner slope or crest the design amount of wave overtopping will determine the stone size and amount of stones to be placed. Riprap has a lot of advantages: it is a relative easy construction method, it does not require a lot of maintenance, it is flexible, sustainable, relatively low in costs and can be re-used at all times. At the other hand, a riprap protection will usually not have the looks of a 'green' revetment.



Figure FS4.1: Rockfill river bank protection



Figure FS4.2: Rockfill spillway

Constructional aspects

- To fulfil filter requirements, a filter fabric of granular filter needs to be placed beneath the layer of riprap.
- Wave overtopping and currents on the inner slope will determine stone size and layer thickness.
- Rockfill of large dimensions (mean diameter of about 0.5 m and up) needs to be placed individually. Smaller rockfill can commonly be placed in bulk.
- Placement can easily be done by hand (small stones), a crane or a floating crane depending on the way the material is brought to the work side.

Operational aspects

Extreme loads, e.g. during storms and floods, will determine the condition of the revetment. After such an event it is advised to inspect the stones from not being dislodged. A rockfill protection can easily be repaired, if stones have been removed by simply adding new stones to the damaged places. Generally, a well-designed riprap slope revetment has a low demand of maintenance. An adverse aspect may be the rather bad accessibility of the riprap by man, equipment and animals by its uneven surface (especially when using large stones).

Environmental aspects

Borrowing of stone from a distant quarry has a negative impact on the environment (scars in the landscape, transportation). At the other hand, riprap is extremely durable and can be re-used easily at any time. The loose packing of riprap, its irregular shape and neutral colour makes a 'natural' impression allows application in a majority of cases. The development of a vegetation cover over a riprap protection is strongly dependent of e.g. the riprap size, the filling rate of the voids and the conditions. A negative aspect of the use of large riprap is that it is not easily accessible for men and animals.

Examples

All over the world riprap revetments have widely been used in coastal defences (outer slope), as river bed and bank protection, river training works and the banks of navigation canals. Riprap placed at the crest and inner slopes of embankments occurs at rockfill spillways of reservoir dams.

Available knowledge / knowledge gaps

The dimensioning and application of riprap protections is widely known. Special situations, e.g. highly turbulent flow and wave overtopping, may still require additional investigations, e.g. in scale models. Knowledge of rockfill spillways (overflow) should be extended to include the highly instationary flow of overtopping waves, for application at the crest and inner slope of coastal defences.

Some relevant references are stated below:

- A.Balkema. 1995. Manual on the use of rock in Hydraulic Engineering. Center for Civil Engineering Research Codes, CUR/RWS, Netherlands, Report 169.
- Technische Adviescommissie voor de Waterkeringen, Leidraad keuzemethodiek dijk- en oeverbekleding. TAW, VNC, VBW-asfalt, Delft 1988.

- CUR-Publication 192, Rockfill application in practice; part 1: Production, applicance and quality Assurance, CUR, Gouda, may 1998 (in Dutch)
- CUR-Publication 200 en 2002, Environmentally friendly banks, CUR, Gouda, 1999 (in Dutch).

Cost indication

The requirements with regard to the quality of the applied riprap are high in most cases: since the costs of transport for high quality riprap may be a major factor, this will make riprap a relatively expensive material. Nevertheless, in the Netherlands riprap has been applied economically, using certain classes and grading of riprap suitable for practical application. The costs, including installation, (price indication year 2000) are roughly as follows: € 10 / m² for a 50/150 mm grading, € 15 / m² for a 80/150 mm grading and € 20 / m² for a 5-40 kg grading. The cost for a 40-200 kg grading will be in the order of magnitude of 35 / m². Additional costs are for removal of the present protection (e.g. € 5 / m² and up) and levelling of the subsoil.

FACTSHEET 5: Pitched revetments

Application

Pitching is the dense placement of loose elements of (nearly) equal shape and size in a regular way. Stones can be of e.g. basalt, granite and limestone. Additionally concrete tiles, blocks (usually of a 'column' type) can be used. Commonly these elements will be placed on a layer of fine quarry run or gravel. In The Netherlands, pitching with natural basalt is the traditional type of dike revetment of coastal defences. The pentagonal and hexagonal stones are placed by hand or with the help of a machine. It is a time consuming job that needs to be done precisely. Changes in labour legislation, and with only a few skilled labourers left, the basalt pitching has lost its attractiveness. Hence, nowadays especially concrete elements are used, with the aid of special equipment. Pitching can only be applied above the water level, so application on the crest or the inner slope of embankments is feasible.



Figure FS5.1: Craftsmanship; basalt columns placed by hand



Figure FS5.2: Concrete tiles placed by special equipment



Figure F5.3: The placement of special concrete blocks

Constructional aspects

- A stone pitching can be placed on top of a granular filter or directly on clay. Sometimes the latter method was used in former days, but this method gave rise to undermining. In addition, it is important that water pressures underneath the pitching will not build up too strongly: therefore a granular layer is required, rather than a filter cloth (geotextile).
- When placed in the correct way a pitched revetment is a very strong revetment that can withstand heavy loads, e.g. direct wave attack in coastal defences.
- Concrete units can be obtained nowadays in many types: e.g. Basalton, Hydro-block, Haringman-block and others.

Operational aspects

To ensure the quality of the revetment a visual inspection needs to be done regularly: the slope needs to be checked for holes or cracks. If only one block has been dislocated this already means that the total strength of the revetment has decreased significantly. The costs of repair are relatively high due to the special equipment needed, as well as the refitting of many more neighbouring blocks.



Figure FS5.4: Damage to a pitched basalt revetment

Environmental aspects

The dense placement of pitching units results in a flat and utmost regular surface which does not allow for proper settlement of vegetation (except for seaweeds). At the other hand, pitched slopes are part of the cultural landscape of sea defences in the Netherlands. They are easily accessible. In a less-salty environment, e.g. the inner slope of sea defences, vegetation will not settle as well by the lack of voids. An agricultural function, e.g. the grazing of sheep, cannot be fulfilled therefore.

Examples

At a major part of the outer slopes of the primary sea dykes in the Netherlands, pitched revetments are being applied. The website of Greenbanks (www.greenbanks.nl) gives some nice examples of applications.

Available knowledge / knowledge gaps

Practical design guides for pitching stone are widely available. It should be noted that most of these guidelines are for design of the outer slope and the translation towards optimal design for the inner slope still has to be made. The following references can be used to gather some additional information:

- CUR-Publication 168a; Bank protection materials, CUR, Gouda, 1994 (in Dutch)
- CUR-Publication 200 en 202, Environmentally friendly banks; CUR, Gouda, 1999 (in Dutch)
- GreenBanks Erosion Control Systems [<http://www.greenbanks.nl>]
- CUR-Publication 155; Handbook for designing of pitched slope revetments, Gouda, 1992 (in Dutch).

Cost indication

Costs depend strongly on the accessibility of the construction site and the size of the project. In general the costs of placed block revetments are quite high. As an example: the costs of a hydro block revetment may roughly vary in between € 40 / m² (for a stone height of 15 cm) to € 75 / m² (for a stone height of 35 cm). Additional costs are for removal of the present protection (e.g. € 5 / m² and up) and levelling of the subsoil. Prices for hydro blocks with an open top layer (so called eco blocks) are about € 10 / m² higher.

FACT SHEET 6: Geotextile elements (mattress systems)

Application

Of all geotextile elements serving as a stand-alone slope protection, a mattress type of element seems to be most suitable. Geomattresses are rather flat geotextile elements that are filled within with soil material (e.g. sand). The difference with geotextile systems that are used to reinforce a grass revetment, is that the latter systems are very open systems, whereas a geomattress is a closed system. In the mattress structure, compartments are made (cellular or tube) as to facilitate an even distribution of the fill material and to prevent internal migration of the fill material. Commonly, the geomattress will be covered by vegetation after some time.

A big advantage of the geomattress is the high flexibility: these mattresses adapt easily to settlements of the earthen structures. Another advantage is that the mattress can be filled with local materials, which may be very profitable when other materials (e.g. rockfill material for a standard type of protection) are absent or when these materials are costly by large transportation distances.



Figure FS6.1: Application of a cellular geo-mattress on the outer slope of an embankment

Constructional aspects

- Geomattresses are not applicable when the significant wave height (under direct exposure) is larger than 1,0 m, or when the local flow velocity is larger than 1,5 m/s.
- Traditional filter requirements should be applied, e.g. by considering the type of aggregate used within the mattress to allow for minimum water permeability as to avoid uplifting.
- At the top, the mattress need to be anchored properly, as to avoid sliding off the slope. A common and easy way to do, is to bury the upper side of the mattress.
- The edges and connections of the mattress are vulnerable and have to be finished neatly, e.g. the joining mattresses can be sewed together and the far ends can be fixed with anchors.

Operational aspects

Hydraulic impact is not the only concern for geomattresses. Other threatening factors are: vandalism, direct exposure to sunlight and chemical damage. Wrapping the vulnerable envelope of the mattress (e.g. with soil) is, therefore, important.

After the development of vegetation, the maintenance of the mattress can be rather limited, as the danger for mechanical damage is reduced then (e.g. by vandalism). However, the roots of vegetation can damage the geotextile fabric on the longer run.

Environmental aspects

De good possibilities for the development of vegetation by overgrowing or growing from within, contribute to the possibilities for a natural appearance. The relatively soft and even surface structures (as compared to e.g. a rockfill protection) allows for easy movement of amphibians.

From the protection point-of-view, as well as from esthetical considerations, a proper application is to cover the geomattress with a thin layer of soil or silt that will be covered with vegetation in due time. Obviously, this will only occur under rather sheltered circumstances that allow the vegetation to develop. The geomattress is a 'hidden protection' then that can deploy itself under severe conditions.

Examples

The most experience with geomattresses has been gained in tropical areas, in situations with strong currents and loose top soils, as a means of bank erosion control.

Available knowledge / knowledge gaps

Research on the stability of geomattresses is rather scarce. However, some sources present preliminary design criteria, that allow for a conceptual design, e.g.:

- J.P. de Waal e.a., Alternative open slope protection systems, WL|Delft Hydraulics, 1998 (in Dutch).
- K.W. Pilarczyk, Geosynthetics and geosystems in hydraulic and coastal engineering, 2000.

The experience in Europe with the Geomats is scarce (Nageler Vaart, Krimpener Waard and Loire), hence no good comparison can be made with the performance of other systems. It is recommended to apply and monitor the performance of the Geomat in a pilot project as to demonstrate the technical and economical feasibility.

Cost indication

The costs for construction of the Geomat can be decomposed as follows:

- mattress 30%
- filling material 10%
- filling/installation 50%
- earthwork 10%

An indication of the costs is: € 20 / m²

FACT SHEET 7: Open asphaltic systems

Application

Different types of asphalt mixtures are being used for bank protection (asphalt being a generic term for mixtures of mineral aggregates and a bituminous binder). Of these types, open stone asphalt seems to be the most feasible system, as this system allows for some vegetation growth. Hence, the open asphalt system combines a suitable protection with environmental qualities. The open stone asphalt systems can be installed in-situ or can be applied as a prefabricated mattress.



Figure FS7.1: Placement of a large open stone asphalt mattress with a lifting frame (Bitumarin)



Figure FS7.2: In-situ installation of open stone asphalt with a crane (Eemmeer)

Constructional aspects

- The permeability of open stone asphalt usually is large, requiring a filter in between asphalt and the subsoil, e.g. a geotextile fabric.
- The flexibility of open stone asphalt to follow settlements of the subsoil is good, without losing integrity and strength.
- Open stone asphalt can cope with current velocities of up to 6 m/s.
- The joints between (prefab) mattresses require proper attention, e.g. by connecting the mattresses with liquid asphalt.
- The in-situ construction of open stone asphalt is with hydraulic cranes. Where possible, the layer should be placed in one time. Subsequently, the layer is compressed with the crane.
- For the installation of large prefab asphalt mattresses, special lifting frames are developed. Small mattresses can be installed by a crane.

Operational aspects

Monitoring of open stone asphalt protections needs to focus on damages that may threaten the covering function for the subsoil, especially the occurrence of joints or cracks that cause losing of under laying subsoil particles.

When the damage is small, this damage can be fixed with cold bituminous mixtures. More extensive damage, however, requires the usage of warm asphalt.

The lifetime of open stone asphalt is in the order of magnitude of 25-50 years. Recycling of open stone asphalt is possible, although breaking and sieving of the material is necessary.

Environmental aspects

After some years, at an open stone asphalt protection, vegetation will have developed, above the waterline, e.g. a mixture of grasses and herbs. Dependent on the maintenance, also shrubs and bushes may develop. In all cases, however, the occurrence of too high temperatures at the surface of the asphalt layer should be prevented. This can be realized by a layer of soil on top of the asphalt substrate. Possibly this situation may arise spontaneously, as the rough surface will enable soil particles to be trapped and hence prove a habitat for vegetation.

Examples

Open stone asphalt has been applied widely in practice, especially as bank protection (direct flow and/or wave impact).

At the website of a major asphalt contract, Bitumarin B.V., different combinations of open stone asphalt with 'green bank' development systems are indicated. An attractive combination is e.g. covering with a (temporary) coconut fibre mattress, including pioneer vegetation. The open structure of the underlying asphalt protection will allow for the roots to settle into the voids of the asphalt after decay of the temporary mattress.

Available knowledge / knowledge gaps

Asphalt has been widely used in the Netherlands for more than 50 years in hydraulic construction, especially to mention for protection of the banks of river and coastal defences. Hence, knowledge about adequate application is widely available. New developments focus e.g. on recycling of asphalt and further promotion of the environmental benefits. An important reference in the Netherlands is:

- TAW, Technical report asphalt for water retaining structures, 2002 (in Dutch).

Cost indication

Open stone asphalt can be applied in different thicknesses. As an example: an open stone asphalt system with a thickness of 0.15 m will cost about € 30 / m², inclusive of a geotextile filter fabric (PP fabric type of 750 gr/m²). Additional costs are for removal of the present protection (e.g. € 5 / m² and up) and levelling of the subsoil.

FACTSHEET 8: Impervious asphaltic systems

Application

Apart from open asphaltic systems, protection of the crest and inner slope of defences may be carried out by the construction of impervious asphalt as well. This can be done by applying prefab asphaltic slabs or an in-situ asphalt layer. The latter requires an even bottom. The prefab slabs require a good under layer, e.g. a mineral aggregate layer. special interest should be paid at the transitions and connections of the slabs. The impermeability may result in excessive pressures underneath the layer, hence the thickness of the layer should be large enough to withstand these forces or constructional measures should be introduced to reduce the pressures, e.g. the application of a toe drainage for embankments.



Figure FS8.1: Preparation for asphalt works

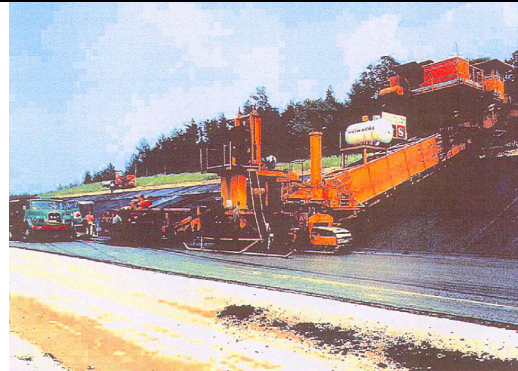


Figure FS8.2: Construction of an asphalt layer on the a slope

Constructional aspects

- Monolith (in-situ) asphalt is applied with the standard road construction equipment.
- For prefab asphalt slabs, special attention should be paid at the joints and connections with other types of revetments.
- The thickness of the layer is determined by the external and internal forces, e.g. wave pressures and excessive water pressures underneath.
- Filter layer may be applied, depends on local conditions and supporting requirements.

Operational aspects

For maintenance it is very important to carry out regular visual inspections. Cracks in the layer endanger the water and ground impermeability and may give rise to piping phenomena (when not noticed, sand will wash out and will form an "invisible" hole underneath). Undermining will reduce the strength of the asphalt section and enlarge the chance that with a next extreme condition the whole section might be washed away. A positive aspect of impervious layers is that visual inspections can easily being carried out (good accessibility, good visibility of damage).

Environmental aspects

A disadvantage of impervious asphalt is that vegetation will not develop, nor is it possible to apply a ground cover at a sloped asphalt revetment (the cover will be washed away from the asphalt). At the other hand, accessibility is perfect. The black colour results in strong heat absorption and hence in surface temperatures of up to 60 degrees Celsius in the summer. From esthetical considerations, the flat black surface does not contribute to the landscape values. A positive aspect from sustainability point-of-view is the possibility of recycling asphalt materials e.g. from roofs (e.g. for the Aquaversal asphalt slab), without significant usage of 'fossil' aggregates. Here, it should be noted that the full environmental impacts should be taken into account, before making negative conclusions on the environmental aspects.

Examples

Many dams of the Delta Works in the Netherlands have local application of asphalt layers at the outer side (above the water line) or on the crest. Examples are the Brouwersdam and the Veersegat dam. Another non-Delta Works example is the Afsluitdijk.

Knowledge and knowledge gaps

As stated before, asphaltic applications have been widely used in the Netherlands as dyke revetments at certain spots in the dyke cross-section (e.g. above the water line, and at the crest). Research publications and design rules for application of asphalt in water defense structures is available and forms an important source of information.

The following references are useful:

- TAW, Guideline for application of asphaltic systems in hydraulic engineering, TAW Delft, 1984, Report no. TR1 (in Dutch).
- Rijkswaterstaat DWW, C.C. Montauban,; Environmental aspects of hydraulic asphalt, Delft, 1982 (in Dutch).
- TAW ; Technical report of asphalt for water defences, 2003, Report no. TR24 (in Dutch).

Cost indication

The costs are strongly dependent on the amount of asphalt (area, thickness) to be applied, as regards mobilisation of equipment. A rough figure for a layer of 0,15 m (inclusive the sub layer) thickness is € 25 / m² (price is inclusive the costs of the sub layer). The prize of a prefab asphalt slab with a thickness of 15 cm is roughly the same.

Additional costs are for removal of the present protection (e.g. € 5 / m² and up) and levelling of the subsoil.

FACTSHEET 9: Concrete systems

Application

The strength and impermeability of concrete makes it a suitable material for shore protection, exposed to extreme wave and flow attack. However, in contrast to asphaltic constructions, concrete has no flexibility at all. This non-flexibility makes it highly sensitive to undermining and subsequent failure. This is especially true for joints and connections. Eventually the slab can break under its own weight or under wave attack.

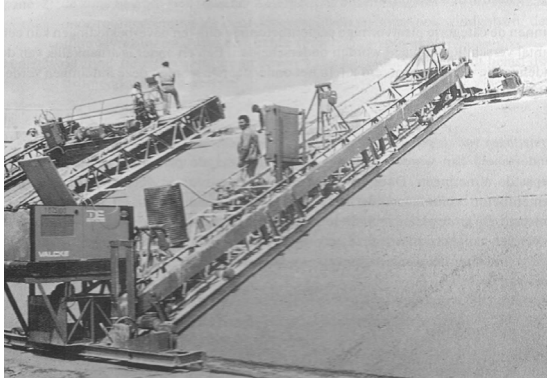


Figure FS9.1: Applying a continuous concrete slab with a spreading machine



Figure FS9.2: Placing concrete with a hydraulic crane

Constructional aspects

- Concrete plates can be constructed at the work site, above the water line, with standard equipment;
- Attention should be paid to provide an even and solid foundation layer.
- Attention should be paid as well to the joints between the slabs and other connections.
- The thickness of the concrete layer is determined by the forces it has to withstand: resulting from wave impact, possible settlement and its own weight.

Operational aspects

When concrete is applied in a marine environment it has to satisfy special conditions: e.g. the usage of sustainable, high quality concrete. The concrete itself does not need inspection; it is the structure as a whole that asks for regular observation. When damage to the joints or some subsidence of the base layer is observed, immediate maintenance action should be taken.

Environmental aspects

Concrete leaves no opportunities for vegetation to settle, unless there are holes or cracks between the sections (which is not desirable from a technical point-of-view). Accessibility is perfect. From an aesthetic point-of-view concrete can be considered as some improvement compared to asphalt, but its monotone looks and hard surface are not a real visual contribution to the environment. Moreover, it will not accumulate so much heat at its surface. However, when applied properly, concrete is very durable and requires almost no maintenance. In addition, it does not require scarce aggregate materials. Concluding, in spite of the 'absence of green', the overall environmental impacts need to be considered, before downgrading the environmental value of a concrete revetment.

Examples

Monolith concrete revetments have only been applied at a few locations in the Netherlands: the revetments of the sea dike of 'Breskens', the river dike of 'Ochten' and the 'Noordoostpolder' IJssellake dike have a concrete lining. These three locations were part of the CUR-commission C 58 test projects. Because concrete slabs do not have any flexibility at all, they are therefore not often used for slope protection. In Germany concrete has been applied in several canal works. Nowadays, usage of a concrete lining is not recommended by the sea defence authorities in the Netherlands.

Available knowledge / knowledge gaps

Knowledge is quite well documented and available. Some relevant references are given below:

- Vereniging Nederlandse Cementindustrie (VNC); Concrete dyke and bank protections, 's Hertogenbosch, 1987 (in Dutch).
- Technische Adviescommissie voor de waterkeringen; Guidelines for concrete revetments, CUR-report 119, VB, Gouda, 1984 (in Dutch).

Costs indication

The costs of concrete are strongly dependent on the amount of concrete to be produced in-situ. As a very rough figure € 50 / m² (price basis 2004) can be taken for a concrete slab with a thickness of 200 mm.

APPENDIX B: PRINTOUT OF DATABASE

References

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Costin, G. : Managed Realignment, Foreshore Recharge and Regulated Tidal Exchange, A literature Review for the ComCoast Project, draft, October 2004.

Pijkereen, L. van: *Zeedijken in een breder perspectief, Onderzoek in het kader van project Blauwe Delta*, MSc Thesis, TUDelft, February 2001 (in Dutch).

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FIRST LEVEL INFORMATION										SECOND LEVEL INFORMATION									
#	TYPE p(ick-let)	NAME / TITLE / PROJECT	AUTHOR / BENEFICIARY	REFERENCE	RESEARCH FRAMEWORK	COUNTRY p	LOCATION	DATE	1 p	2 p	3 p	Availability p	Type of knowledge p	Relevance p	Essential focus (keywords) p				
98	technical data	Golfloop en golfvoetsing bij dijk	J.W. van der Meer	H.2468 / H3051 WL Delt Hydralics in opdracht van de DWW		Netherlands		1987	OVERTOPPING/OVERFLOW			yes: book or report	theoretical	+	wave run-up and overtopping				
99	technical data	Stability of artificial roughness elements and run-up reduction	Piarczyk, K.W.	Proceedings of the twenty-fifth international conference, 1986		Netherlands		1986	OVERTOPPING/OVERFLOW			payable but free abstract	theoretical	+	wave run up				
100	technical data	Design of revetments	Piarczyk, K.W.	Paper, Dutch Public Works Department (RWS)		Netherlands		1988	STRENGTHENING OF DEFENCE			yes: book or report	theoretical	+	design coastal structures				
101	technical data	2-D numerical analysis of near-field flow at low-crested permeable breakwaters	N. Garcia, J.L., Lara, J.J., Losada	Coastal Engineering 51, page 891-1020		Other	Spain	2004	FORESHORE WAVE REDUCTION			yes: book or report	theoretical	+	design low-crested structures				
102	technical data	Surf zone wave overtopping at a topozoidal structure: 1-D modelling and PIV comparison	P.K. Shandilya et al	Coastal Engineering 49, page 485-500		Germany	U.K.	2003	FORESHORE WAVE REDUCTION			yes: book or report	theoretical	+	overtopping				
103	technical data	Stability of scour overtopping on berm breakwaters	A. Torum et al	Coastal Engineering 50, page 212-224		Other	China	2003	FORESHORE WAVE REDUCTION			yes: book or report	theoretical	+	wave transmission				
104	technical data	Random wave run-up on seawalls near dikes and artificial reefs	Mase, H et al	Coastal Engineering Journal, Vol. 46, No. 3		Other	Japan and India	2004	FORESHORE WAVE REDUCTION			yes: book or report	theoretical	+	wave run-up				
105	technical data	In situ measurement of erosion shear stress and geotechnical shear strength of the intertidal seabed	C.W. Watts et al	Estuarine, coastal and shelf science 58, page 611-620		U.K.		2002	FORESHORE WAVE REDUCTION			yes: book or report	proven/practical	+	erosion protection works				
106	technical data	Wave dissipation over macro-tidal saltmarshes, effects of marsh edge topology and vegetation on	I. Miller and T. Spitzer	Journal of coastal research 30, page 506-521		Germany		1997	FORESHORE WAVE REDUCTION			yes: book or report	theoretical	+	erosion protection works				
109	technical data	Optimised design of land reclamation fields for sustainable foreland development	S. Mai and C. Zimmermann	Proc. Of the 3rd Int. Conf. Port Development & Coastal Environment		U.K.		2003	FORESHORE WAVE REDUCTION			yes: book or report	theoretical	+	risk analysis				
110	technical data	Importance of forelands and summer dikes for coastal safety	K. McCornell	HR Wallingford, ISSN 02777060		U.K.		1998	STRENGTHENING OF DEFENCE			yes: book or report	theoretical	+	design coastal structures				
111	technical data	Revetment systems against wave attack - A design manual	M. van der Meert	Wetenschappelijke bijdragen tot de kustbescherming (BR-DLO)		Netherlands		1983	STRENGTHENING OF DEFENCE			yes: book or report	theoretical	+	grass on strength				
112	technical data	Vegetatieparameters bij de ontwerping van duinen	H. Sprangers	Wetenschappelijke bijdragen tot de kustbescherming (BR-DLO)		Netherlands		1983	STRENGTHENING OF DEFENCE			yes: book or report	theoretical	+	grass on strength				
113	technical data	Vegetation dynamics and erosion resistance of sea dikes grassland	M. van de Paved	Ph.D. Thesis, Wageningen Agricultural University, ISBN 90-5482		Netherlands		1999	STRENGTHENING OF DEFENCE			yes: book or report	theoretical	+	grass on strength				
114	technical data	Het ontwerpen van een bekkering voor een zeedijk	H. Sprangers	Ph.D. Thesis, Wageningen Agricultural University, ISBN 90-5482		Netherlands		1999	OVERTOPPING/OVERFLOW			yes: book or report	theoretical	+	overtopping				
115	technical data	Data on wave transmission due to overtopping	J.W. van der Meer	WL Delt Hydralics report H 866 prepared for CUR C57		Netherlands		1987	STRENGTHENING OF DEFENCE			yes: book or report	theoretical	+	waves and strength of dikes				
117	technical data	Praktijkproef met Enkammen in het Grevelingenmeer 1974-1986	Anonymus	WL Delt Hydralics rapportnummer H 726		Netherlands		1983	OVERTOPPING/OVERFLOW			yes: book or report	theoretical	+	oblique wave transmission				
118	technical data	Waterbeweging op taluds; invloed van berm, tuindek, omdiep, voorland en schieve lang-korkeamm	J.W. van der Meer en J.P. de Waal	Proceedings of the 8th International Conference on Coastal and Port Engineering in Developing Countries		Netherlands		1988	STRENGTHENING OF DEFENCE			yes: book or report	theoretical	+	design low-crested structures				
119	technical data	Design of low-crested (submerged) structures	Piarczyk, K.W.	Ph.D. Thesis, Delft University of Technology		Netherlands		2003	STRENGTHENING OF DEFENCE			yes: book or report	theoretical	0	grass on strength				
120	technical data	Vegetation dynamics and erosion resistance of sea dikes grassland	J.T.C.M. Sprangers	Ph.D. Thesis, Landbouwwetenschappelijke Universiteit Wageningen		Netherlands		1988	STRENGTHENING OF DEFENCE			yes: book or report	theoretical	0	grass on strength				
121	technical data	Vegetation dynamics and erosion resistance of sea dikes grassland	J.T.C.M. Sprangers	Ph.D. Thesis, Landbouwwetenschappelijke Universiteit Wageningen		Netherlands		1988	STRENGTHENING OF DEFENCE			yes: book or report	theoretical	0	grass on strength				
122	technical data	Erceomodellen voor dijken bij golfaanval. Verdere modellering in het kader van SPRINT en het pro	J.W. van der Meer	Infraam report 1256		Netherlands		2000	STRENGTHENING OF DEFENCE			yes: book or report	theoretical	0	waves and strength of dikes				
123	technical data	Meeremmen resistente middelen restier bleefactor	M. Klein Breisler	Workshop 'Steenbekeldijken en restierke'		Netherlands		2002	STRENGTHENING OF DEFENCE			yes: book or report	hyothetical	0	waves and strength of dikes				
124	technical data	Restierke van steenzettingen	J.W. van der Meer, P. Tones and H. de Waal	www.infraam.nl products/services/publications		Netherlands		2002	STRENGTHENING OF DEFENCE			yes: book or report	hyothetical	0	waves and strength of dikes				
125	technical data	A code for dike height design and examination based on wave run-up and wave overtopping	J.W. van der Meer, P. Tones and H. de Waal	www.infraam.nl products/services/publications		Other		1998	OVERTOPPING/OVERFLOW			yes: digital	proven/practical	0	waves and strength of dikes				
126	technical data	Analysis of wave transmission behind low-crested structures using neural networks	A. Pranzos, B. Briganti, J.W. van der Meer and B. Jonkman	www.infraam.nl products/services/publications		Other		2004	FORESHORE WAVE REDUCTION			yes: digital	proven/practical	0	wave transmission, neural network				
127	technical data	Overstromingsrisico's: een onderzoek naar de toepasbaarheid van rekenmodellen	H. Jonkman	MIS-theses Delft University		Netherlands		2001	OVERTOPPING/OVERFLOW			yes: book or report	theoretical	0	risk analysis				
128	technical data	Shallow foreshore wave height statistics. A predictive model for the probability of exceedance of	Craig M. Ullmann, Colorado State University	ASCE, Joint Conference on Water Resource Engineering and Wat		Netherlands		1988	FORESHORE WAVE REDUCTION			yes: book or report	proven/practical	0	wave boundary conditions				
131	technical data	Stability of Rounded Riprap in Overtopping Flow	Franco C. Franco L.	Journal of waterway port coastal and ocean engineering ISSN 073		Other	USA	2000	FORESHORE WAVE REDUCTION			payable but free abstract	proven/practical	0	stability of riprap				
132	technical data	Overtopping formulae for caisson breakwaters with nonbreaking 3D waves	Chian E. Yip, Franck A.C.	Coastal Engineering 1990 Conference Proceedings		Other	Italy	1990	OVERTOPPING/OVERFLOW			payable but free abstract	proven/practical	0	overtopping				
133	technical data	Beach nourishment: a method for shoreline conservation with natural materials	Rijn van Weert, P. A.	International Design and port construction 1809 ISSN 0284-4835		Belgium		1986	FORESHORE WAVE REDUCTION			payable but free abstract	proven/practical	0	beach nourishment				
134	technical data	Wave transmission for beach nourishment projects	Work, P. A.	Coastal Engineering 1997, ISSN 0378-3839		Other		1997	FORESHORE WAVE REDUCTION			payable but free abstract	theoretical	0	beach nourishment				
136	technical data	Wave transmission for beach nourishment projects	S.A. Hughes	Coastal Engineering 51, page 1085-1104		Other	U.S.A.	2004	OVERTOPPING/OVERFLOW			yes: book or report	theoretical	0	wave run up				
138	technical data	Nearshore wave prediction by coupling a wave model and statistical methods	T. Kobayashi et al	Coastal Engineering 51, page 297-308		Other	Japan	2004	FORESHORE WAVE REDUCTION			yes: book or report	theoretical	0	wave reduction				
139	technical data	SP-Hes model for numerical investigation of wave interaction with partially immersed breakwater	D.T. Bergado	Computers and Geotechnics 30, page 517-534		Other	Thailand	2003	STRENGTHENING OF DEFENCE			yes: book or report	theoretical	0	wave transmission				
140	technical data	The interaction mechanism and behavior of hexagonal wire mesh reinforced embankment with	D.T. Bergado	Computers and Geotechnics 30, page 517-534		Other	Thailand	2003	STRENGTHENING OF DEFENCE			yes: book or report	theoretical	0	reinforced earth systems				
141	technical data	Golfdeining door net	H.J. Verheij	WL Delt Hydralics rapportnummer Q 2037		Netherlands		1995	FORESHORE WAVE REDUCTION			yes: book or report	theoretical	0	wave damping				