FloodProBE

SEVENTH FRAMEWORK PROGRAMME

The Performance of Vegetation on Flood Embankments

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Summary

The grass surface cover on a flood embankment protects against soil erosion and can either prevent breach or delay the onset of breach. Assessing the performance of grass in this context is therefore an important aspect of the overall performance assessment for flood embankments. The importance of grass cover performance is increased if “acceptable overtopping / overflow” is permitted, and climate change effects pose an increasing pressure upon the performance of grass cover on flood embankments.

The longer term aim of this research action is the development of extended or revised guidance based upon a review of international research results and existing grass performance data from the last 25 years. Specific research actions comprised:

- A review of project initiatives related to the performance of grass
- Investigation into the grass performance data collected at the USDA Stillwater centre over the past 20 years, to identify what aspects might be relevant to European practice
- Confirmation of existing European and US guidance on grass performance, followed by identification of either (i) updates to guidance using existing international research findings or (ii) clarification of longer term R&D needs to improve knowledge and performance of embankment grass cover layers (See Section 7 of this report).

Section 4 provides a summary of relevant project initiatives identified during the review. A template has been used to provide consistent information on each initiative. Section 5 summarises conclusions from this review, namely that whilst there are a lot of research projects investigating the effects of grass on flow, there are very few documents providing guidance on the effects of flow on grass. Three methods were identified, all of which are interlinked to some degree. These methods comprised (i) CIRIA Technical Note 71; (ii) CIRIA Report 116 and (iii) USDA Handbook 667.

Research relating to grass performance under wave overtopping – rather than overflow – is currently being investigated through the Dutch SBW programme (2007 – 2017). Initial results start to provide revised guidance for grass performance under wave overtopping conditions. An overview of this work is provided in Section 6.

An investigation into the original research analyses and data underpinning the CIRIA and USDA methods concluded that the original data could no longer be accessed. This earlier research was undertaken in the 1970s and 1980s hence data was not necessarily stored electronically. Hence, rather than reanalysis of the original data, the performance of the three methods identified were compared by applying each to two test cases where embankments with grass cover were failed under controlled conditions. The results (Section 7) highlight the differences between these methods in relation to a range of parameters that were considered relevant to embankment and grass cover performance.

Two conclusions from this review were:

1. The CIRIA 116 design curves consistently predicted quicker grass failure times than the CIRIA Technical Note 71 data. This is consistent with the inclusion of a factor of safety into the CIRIA 116 performance curves (Morris et al, 2010). Users of the CIRIA 116 curves should note that a factor of safety has been included since the relevance of this differs if the curves are used for design or performance / reliability assessment (with design leading to a safer design, whilst with performance assessment, leading to a pessimistic assessment of behaviour).

2. The USDA approach incorporates the plasticity index, which reflects to a degree, the soil erodibility (Morris, In Prep). This shows a significant variation in performance, as soil erodibility reduces, whereas the CIRIA methods show no variation, because soil parameters are not considered. It would seem logical that the physical process of grass erosion, with the removal of roots from the soil, would also relate to the resistance of the underlying soil to erosion. The trend in breach analysis is towards the use of soil erodibility in order to improve representation of the embankment performance. Similarly, with the likely trend being towards design or planning for acceptable over flow during increasingly extreme flood events, adoption of a method that includes representation of soil erodibility would seem sensible.

However, the extent to which US grass performance data is valid in Europe remains unclear. Where grass performance is related to root density, soil strength etc. it would seem ‘transferable’, but research looking at this issue does not appear to have been undertaken.

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1 The FloodProBE Project

FloodProBE is a European research project with the objective of providing cost-effective solutions for flood risk reduction in urban areas. FloodProBE aims to develop technologies, methods and tools for flood risk assessment and for the practical adaptation of new and existing buildings, infrastructure and flood defences leading to a better understanding of vulnerability, flood resilience and defence performance. This research supports implementation of the Floods Directive through the development of more effective flood risk management strategies. The work is being undertaken in close partnership with industry, and is utilising pilot sites across Europe, to help provide practical industry guidance and cost effective construction solutions.

The FloodProBE activities have been structured according to the following work packages (WP):

- *WP2* addresses issues related to the vulnerability understanding and assessment of the vulnerability of urban areas or systems.
- *WP3* deals with failure modes and the assessment and identification of weak spots in urban flood defences.
- *WP4* investigates cost-effective construction technologies and concepts for improving the performance of existing and new flood defences and for increasing the flood resilience of urban systems and assets
- *WP5* supports integration of the research and newly developed knowledge into existing decision support models or systems, the production of industry guidance and the interaction and integration of pilot site studies across Europe.
- The dissemination and stakeholder-involvement activities are addressed under *WP6* whilst *WP1* comprises all activities related to the management of the consortium.

The work described in this report is part of *WP3*.

2 Introduction

Flood defences are key elements within a flood risk management system. They provide protection to people and assets but always need to be maintained at an acceptable level of performance. With man made pressures such as urban development or natural pressures such as climate change, it is important to find cost effective solutions to maintain the performance of flood defences to the appropriate level of flood risk.

In order to identify these cost effective methods, it is essential to understand the performance of the different types of flood defences and their likely failure modes. This is the aim of research under *WP3* of the FloodProBE project. The two key goals of this research are:

1. To improve fundamental understanding of erosion failure processes that have proven to be critical in recent major flood events in urban areas.

To increase the effectiveness and efficiency of risk based asset management by applying and refining innovative and cost-effective measurement and monitoring technologies in combination with other information sources for the identification of high risk areas (weak spots).

To achieve the first objective, the following topics related to the flood defences performance have been investigated:

1. Internal erosion.
2. Structure transitions.
3. Performance of vegetation during flooding.

This report focuses on the performance of vegetation during flooding, i.e. it attempts to address the questions of how well grass can protect the underlying soil when subjected to flow and what are the limiting loadings that will remove (or partly remove) the grass cover and halt its erosion prevention function. In this context, vegetation is taken to mean grass cover on earth flood embankments. Hence, this research does not address the performance of woody vegetation or trees on flood embankments. In many countries such vegetation is not permitted to grown on flood embankments.

2.1 Aims and objectives

The grass surface cover on a flood embankment protects against soil erosion and can either prevent breach or delay the onset of breach. Assessing the performance of grass in this context is therefore an important aspect of the overall performance assessment (and hence flood risk assessment) for flood embankments.

The significance of grass cover performance is increased if “acceptable overtopping / overflow” is permitted as part of flood risk management practice. Under such conditions, the estimated performance of the flood embankment will include and depend upon the performance of the grass cover. The effects of climate change appear to be leading towards more extreme conditions for both hydraulic loading (magnitude of flood event) and climatic conditions (prolonged wet and dry periods). These changes pose an increasing pressure upon the performance of grass on flood embankments. Not only do the hydraulic load conditions increase, but the environment pressures affecting the quality and stability of the grass are also changing.

The broad aim of this research action is the development of extended or revised guidance based upon a review of international research results and existing grass performance data from the last 25 years.

2.2 Scope of work

Specific research actions on grass performance comprised:

- A review of project initiatives related to the performance of grass (See Sections **Error! Reference source not found.**, 4 and **Error! Reference source not found.** of this report).
- A review of current state of the art research for grass performance under wave overtopping (see Section 6)
- Investigation of grass performance data collected at the USDA Stillwater centre over the past 20 years, to identify what aspects might be relevant to European practice (See Section 7 of this report).
- Confirmation of existing European and US guidance on grass performance, followed by identification of either (i) Updates to guidance using existing international research findings or (ii) clarification of longer term R&D needs to improve knowledge and performance of embankment grass cover layers (See Section 8 of this report).

3 Summary of the Literature Review

3.1 Introductory remarks

Grass is considered to have good performance if it prevents erosion of the underlying soil and ultimately any damage to the flood defence. Determining the loading(s) up to which grass remains in place, offering protection to the structure, is one of the primary aims of the designer and asset manager.

The hydraulic performance of grass on flood embankments can be assessed by the loading(s) to which the grass and embankment are subjected. These loadings fall mainly into the following categories: overtopping, overflow and rainfall runoff.

In general the hydraulic performance of grass can be considered in terms of:

1. its erosion resistance, by means of a “maximum permissible velocity” of the flow or the “effective shear stress” that a grass lined structure can withstand;
2. its resistance to the flow, usually by means of a coefficient of frictional resistance such as Manning’s n.

Both concepts are useful and complementary: the erosion resistance indicates if the grass cover can protect the underlying soil and the resistance (or friction factor) allows the calculation of the flow depth/velocity/rate. For the case of flood embankments, determining the erosion resistance is the primary aim, whereas the resistance to the flow becomes more relevant to the design of grassed channels because it allows the determination of the conveyance of a channel. However, the knowledge of the resistance of grass is also important in the context of flood embankments as it is required in certain methodologies for the determination of the effective shear stress, for example, and allows the estimation of how much flow can reach areas behind the defences and how fast it can reach them.

It has been found that much of the literature on the hydraulic performance of grass relates to resistance and derives from work on grassed channels rather than grassed embankments. Despite some differences in terms of water velocity and depth, this research is likely to be relevant for the assessment of grass resistance in other situations such as in flood embankments. In particular, there are synergies between shallow grassed channels used intermittently for flow discharge and the flow overtopping flood embankments. On this basis, some of the sources summarised in section 3.2 relate to channels.

As a general indication, Coppin & Richards (1990) have suggested permissible velocities (which depend on the soil, the density of grass cover and the longitudinal gradient of the channel/slope) in the range 1.2m/s and 2.1m/s for good grass cover. It has been found that the duration of the flow is a relevant parameter in the erosion of channels that are intermittently subjected to flow, which is the case of flood embankments. Even without reinforcement, grassed surfaces can withstand considerably high velocities for short durations: almost 4m/s for 1 hour or 3m/s for 2 hours. Long term stability is generally achieved if flow velocities remain below 1m/s. (Hewlett et al, 1987).

The relatively recent development of the wave overtopping simulator has encouraged testing of real flood embankments, in-situ, by the controlled release of water down the embankment slope (van der Meer, 2006, van der Meer et al., 2009). This is helping to clarify how the in-situ performance of grass varies with a range of factors relating to the design and state of the flood embankment.

3.2 Literature review summary

The performance of grass during flooding has been studied by a number of organisations in Europe and worldwide. In order to build upon the knowledge gained from these studies, a literature review was undertaken. The main objectives of this review were to:

- Identify major work that was or is being undertaken to assess vegetation performance during flooding.
- Undertake critical analysis of the work identified above.
- Gain greater understanding of the performance of grass during flooding.
- Recognise gaps in knowledge.
- Propose a way forward (to improve performance guidance for use in flood risk management).

The main source of information for the literature review was through Internet web based searches. However, knowledge and links from the wider FloodProBE team also contributed. A detailed list of information sources / searches is provided in Appendix 1.

The literature review was structured according to two geographic regions:

1. Region 1: Europe
2. Region 2: The rest of the World)

Figure 3-1 provides a graphical summary of the initiatives found within each of these regions, listed chronologically. Whilst there are numerous studies into the effects of vegetation on flow (not listed here), there are considerably fewer detailing the performance of grass under overflow conditions.

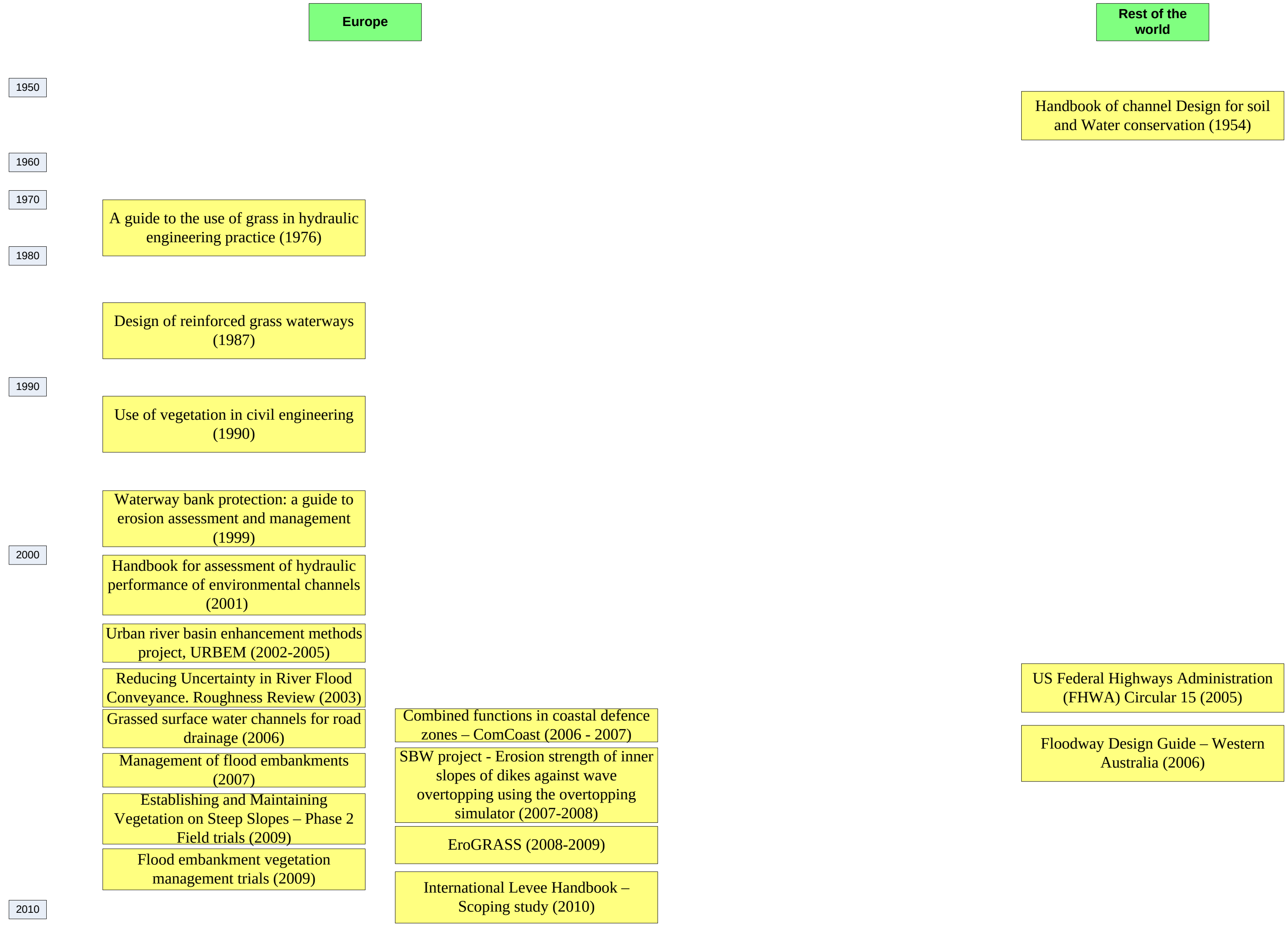


Figure 3-1: Main literature identified

4 Review of literature and data

This section provides a detailed description of the literature review that was undertaken. The information is split according to the two regional groups, namely Europe and the USA and Other (incorporating any initiatives from outside of Europe and the US).

4.1 Region 1: Europe

In Europe, the review has identified a number of initiatives in the UK, Netherlands, Germany, Denmark and France in addition to a series of specific EU funded projects. These are listed below and summarised in the following tables in chronological order.

4.1.1 A guide to the use of grass in hydraulic engineering practice (1976)

Project Description:

This technical note was published by the Construction Industry Research and Information Association (CIRIA) in the UK in 1976 (TN 71). The note provides guidance on the use of grass to stabilise surfaces subject to erosion by the intermittent flow of water. For structures like dam emergency spillways, river embankments and by wash channels, the frequency of occurrence of flow can be so low that expensive concrete works are not justified. The main purpose of the guide is to help the water engineer to decide whether a grass lining is appropriate, by providing information on the erosion resistance and frictional resistance of grasses. The note includes recommendations on grass mixtures, establishment and management procedures. The main part of the work relates to freshwater situations, but a section is devoted to the case of coastal embankments.

Methodology

The note focused on two aspects of grass which are:

1. The resistance to erosion, which was expressed in terms of velocity-duration envelope (i.e. the length of time for which a grass surface can safely withstand a given flow without dangerous erosion). Figure 4-1 shows a velocity - duration diagram which is based on information from various laboratory investigations (See sources of information section below).

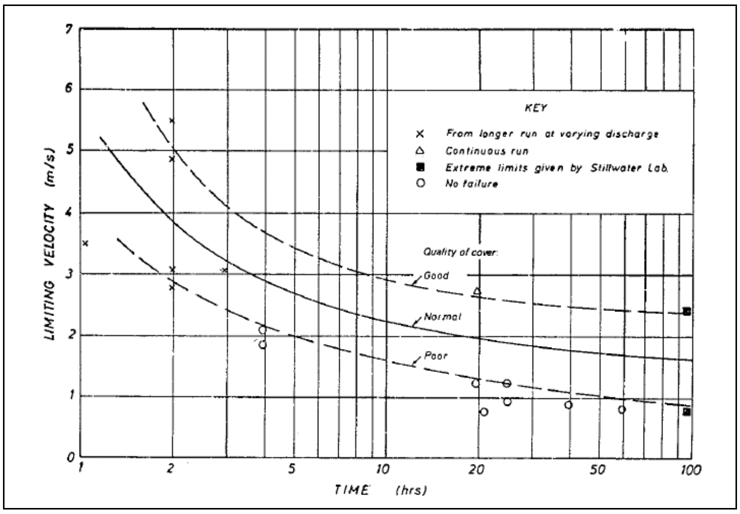


Figure 4-1: Erosion resistance of grass

2. The hydraulic frictional characteristics of the grass prior to erosion, and any variation there may be in friction with the height and density of grass and the velocity or depth of flow. The note divided the flow over a vegetative surface into three basic regimes:

   - When the flow depth is significantly less than the height of the vegetation, which is not deflected.

- When the flow depth is close to or greater than the height of the vegetation, which deflects and oscillates.
- When the velocity is high enough to lay the vegetation down and a relatively smooth, stationary surface is presented to the flow. The effective height of the vegetation is then considerably less than its natural height.

The note recommended the use of a procedure for determining the flow in grass-lined channels based upon that developed by the Stillwater Laboratory in Oklahoma. This method is based on Manning's equation where Manning's roughness coefficient (n) is related to flow in the form of a flow parameter (VR) as follows:

$$V = \frac{1}{n} R^{\frac{2}{3}} S^{\frac{1}{2}}$$
$$So \rightarrow n = f(VR)$$

where V is the mean velocity, R is the hydraulic radius and S is slope of the embankment or channel bed.

The physical characteristics of the grass which are defined by height and density are also taken into consideration for 5 different categories (A to E) as shown in Figure 4-2. For details of these categories see Table 4-1. In this context Manning's coefficient includes the effect of all factors tending to retard flow and is referred to as a 'retardance coefficient'.

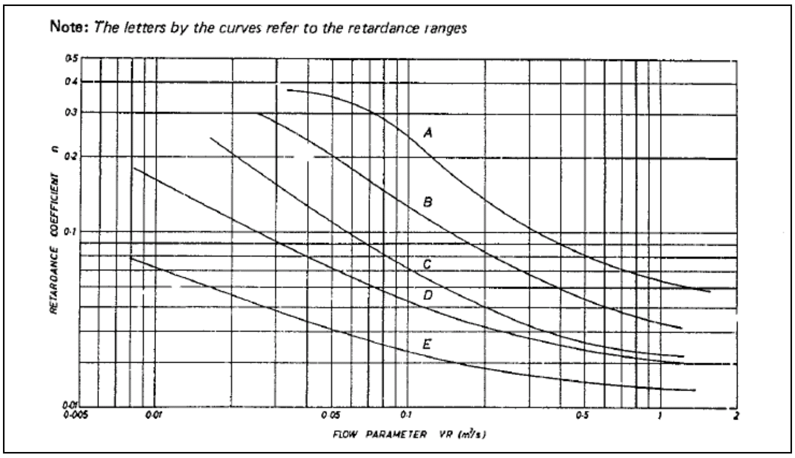


Figure 4-2: Frictional resistance of grass

The note also discusses the botanical characteristics of grass that is used in hydraulic engineering practice such as the root, leaves, stem and life span. It also gives general considerations that govern the choice of grass. It also gives guidance on suitable grasses and mixtures for spillways, by wash canals and river banks.

Limited information has been also presented on coastal embankments. This was based upon the observation following the disastrous East Coast floods of 1953 by the UK and Dutch authorities. With particular reference to grass covers, it was noted that on the one hand grass provided an effective defence against scour, but on the other hand, the presence of vegetation may have intensified shrinkage and fissuring of the surface, thereby contributing to the seepage that led to failure of the cover. It was also reported that Dutch authorities found that water velocities of up to 2 m/s caused little damage to grass cover.

Table 4-1: General guide to vegetal retardance categories

Condition	Average length	Category
Good	Longer than 30 in	A
	11 in to 24 in	B
	6 in to 10 in	C
	2 in to 6 in	D
	Less than 2 in	E
Fair	Longer than 30 in	B
	11 in to 24 in	C
	6 in to 10 in	D
	2 in to 6 in	D
	Less than 2 in	E

Site trials of species and varieties which might be appropriate in the UK have been also undertaken within this study. The overall purpose of these trials was to make a comparative appreciation of the main types of the many available grass mixtures under a range of typical field conditions but no hydraulic assessment was carried out.

Advantages : The methodology is clear and simple

Disadvantages: Methodology is based on data from the US and Australia. No data for reinforced grass.

Question	***Yes / No***	***Comments***
Does the research provide design and / or performance guidance?	Yes	It provides guidance on the use of grass to stabilise surfaces subject to erosion by intermittent flow of water. The method also considers the erosion and friction resistance of grass.
Is the research relevant to conditions in Europe? (i.e. Grass type; test conditions, etc)	Yes	Trials have been undertaken to test grass mixtures in the UK. Although, hydraulic properties of grass has been obtained from research in the US and Australia. They give guidelines to the limitations of (all) grasses of

		similar growth habit.
Is the guidance generally applicable? (If not list specific conditions such as wave overtopping, overflow, steep slopes etc. in the comments box)	Yes	Mainly for spillways, by wash channels and river banks. Some limited information was presented for sea banks.
Could the research provide access to grass performance data? (Explain how and what data in the comments box if applicable).	No	
Does the research have an ongoing programme of work? (List in the comments box if applicable)	No	

Source of information / further information:

Whitehead, E., 1976. “A Guide to the Use of Grass in Hydraulic Engineering Practice”. Technical Note 71, Construction Industry Research and Information Association, London.

CORNISH, B.A., YONG, K.C., and STONE, D.M., 1967. “Hydraulic characteristics of low cost surfaces for farm dam bywash spillways” University of New South Wales Water Research Laboratory, Report 93

US Soil Conservation Service, 1954. “Handbook of channel design for soil and water conservation”, Publication SCS-TP61.

EASTGATE, W., 1969 “Vegetated stabilization of grassed waterways and dam bywashes”, Water Research Foundation of Australia, Bulletin 16.

YONG, K..C. and STONE, D.V., 1967. “Resistance of low cost surfaces for farm dam spillways”, University of New South Wales Water research Laboratory, Report 95.

COX, M.B., 1942. “Tests on vegetated waterways”, Oklahoma Agricultural Experimental Station, Technical Bulletin T-15.

4.1.2 Design of reinforced grass waterways (1987)

Project Description:

This report was published by CIRIA in the UK in 1987 (CIRIA Report 116). It sets out the procedure and principles for the planning and design of plain and reinforced grass waterways. The report focuses on the hydraulic, geotechnical and botanical design aspects of the following grass types:

- Plain with poor, average and good cover.
- Reinforced with geotextile or concrete.

Methodology

The report recommends the use of limiting velocity vs overflow duration curves for the design of plain and reinforced types. Figure 4-3 shows the curves proposed in this report. This approach is similar to what was proposed by the study described above in Section **Error! Reference source not found.**, however, the curves shown in Figure 4-3 are based on a number of trial tests that have been undertaken within this study at the Jackhouse reservoir in the UK. Full details of the tests are given in the project records on the field trials by Salford Civil Engineering Ltd. and Geostructures Consulting (See sources of information section below).

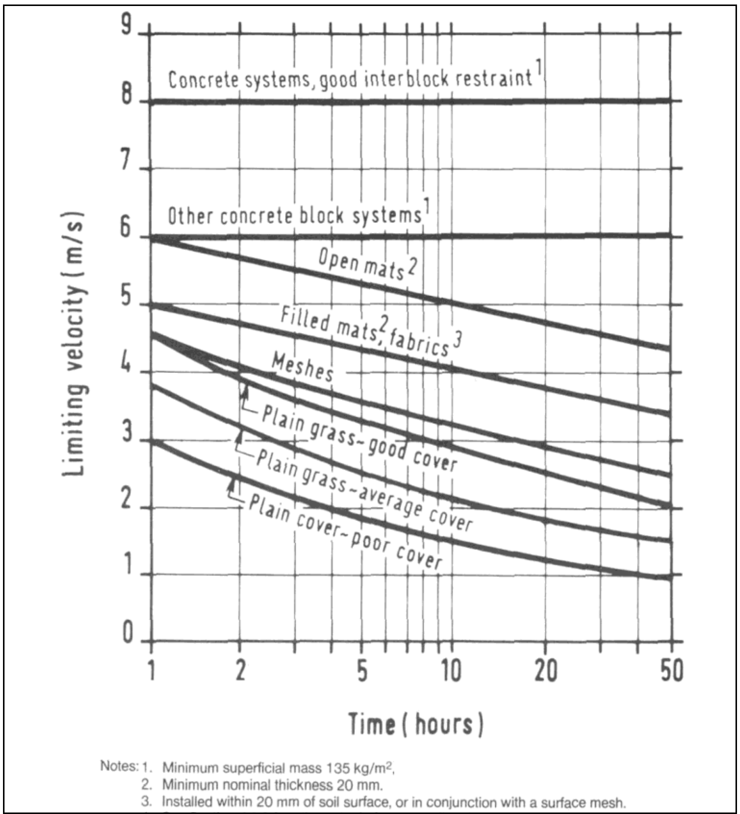


Figure 4-3:Recommended values for erosion resistance of plain and reinforced grass

The study also recommended retardance coefficients for grassed slopes steeper than 1 in 10 as shown in Figure 4-4. For slopes flatter than 1 in 10 the VR method recommended in Section 4.1.1 was also proposed by this study.

Considerations relating to specification, construction and on-going management are also discussed with various reinforcement systems available in the UK described. It should be also noted that recent research under the EC funded project FLOODsite (Young, 2005 and Morris et al, 2010) recommended the use of this data for grass performance analysis.

Advantages: The design method is clear and simple.

Disadvantages: Through simplicity, there are no parameters relating to type of grass, root density or soil type. (Quality Good, Average & Poor is allowed for). There appear to be in built factors of safety. Performance curves are based upon a limited amount of base data.

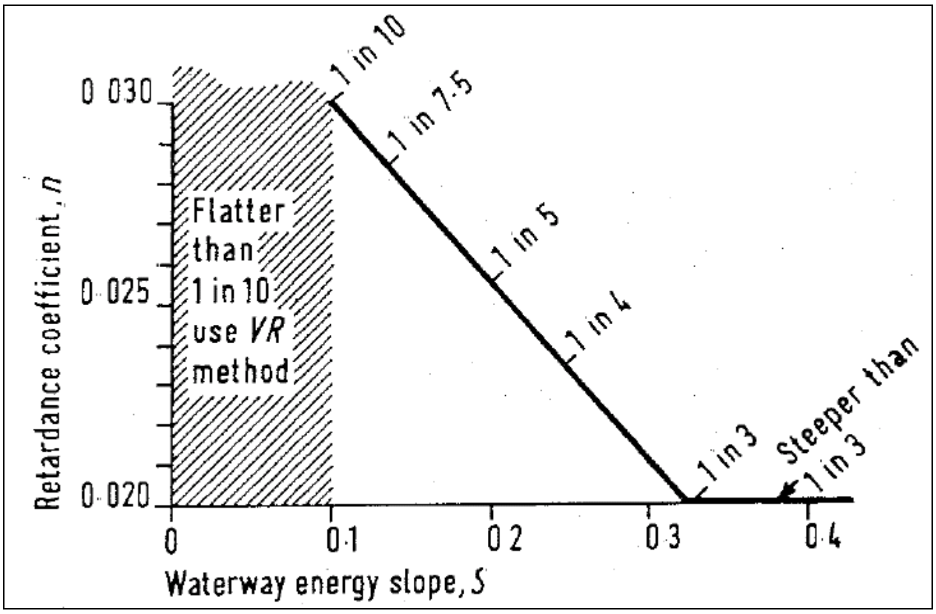


Figure 4-4: Recommended retardance coefficients for grassed slopes steeper than 1 in 10

Question	***Yes / No***	***Comments***
Does the research provide design and / or performance guidance?	Yes	Provides design curves for the performance of grass under overflow conditions. The method also considers the erosion and friction resistance of grass.
Is the research relevant to conditions in Europe? (i.e. Grass type; test conditions, etc)	Yes	Data is taken from tests performed in the UK
Is the guidance generally applicable? (If not list specific conditions such as wave overtopping, overflow, steep	Yes	Design curves are for overflow conditions. No wave overtopping or combined wave overtopping and

slopes etc. in the comments box)		overflow.
Could the research provide access to grass performance data? (Explain how and what data in the comments box if applicable).	No	Attempts to track the base data have failed. Research was undertaken too far in the past to recover this data.
Does the research have an ongoing programme of work? (List in the comments box if applicable)	No	

Source of information / further information:

Geostructures Consulting, 1986, "In-situ evaluation of shear strength of armour layers", Project Record 352 CIRIA.

Hewlett, H. W., Boorman, L. A., and Bramley, M. E., 1987 "Design of reinforced grass waterways", Construction Industry Research Information Association (CIRIA) report number 116.

Morris, M.W., Boorman, L.A. and Simm, J.D. (2010) 'Just how important is grass cover?', British Dam Society 16th Biennial Conference, University of Strathclyde, Scotland,23-26th June 2010.

Salford Civil Engineering LTD, 1986, " Hydraulic field trials at Jackhouse Reservoir", Project Record 352

Young, M.J. (2005) Wave overtopping and grass cover layer failure on the inner slope of dikes, UNESCO-IHE Institute for Water Education, Delft. MSc.

4.1.3 Use of vegetation in civil engineering (1990)

Project Description:

This report was first published by CIRIA in 1990 and then reprinted in 2007. It introduces a range vegetation uses that are relevant to the UK construction industry. The majority of these uses relate either to the restraint of surface soil particles or the stabilisation of a soil mass.

The report provides an understanding of the principles and procedures involved in the engineering use of vegetation (i.e. bioengineering) and how these can be employed. It also identifies areas where the engineer must seek specialist advice on the selection and establishment of vegetation.

The principles and procedures brought out in the report are applicable to a wide range of climates and soils, but the applications presented, together with specific information on climate, soils and plant species, have been selected to reflect UK conditions.

Advantages : Provides general guidance to the engineer on bioengineering

Disadvantages: Focus is not on grass performance

Question	***Yes / No***	***Comments***
Does the research provide design and / or performance guidance?	Yes	
Is the research relevant to conditions in Europe? (i.e. Grass type; test conditions, etc)	Yes	UK conditions
Is the guidance generally applicable? (If not list specific conditions such as wave overtopping, overflow, steep slopes etc. in the comments box)	Yes	
Could the research provide access to grass performance data? (Explain how and what data in the comments box if applicable).	No	
Does the research have an ongoing programme of work? (List in the comments box if applicable)	No	

Source of information / further information:

Coppin, N.J, Richards, I.G., (1990), The use of vegetation in civil engineering. CIRIA, Butterworths edition.

4.1.4 Waterway bank protection: a guide to erosion assessment and management (1999)

Project Description:

This guide provides a framework for the design of bank protection in flood defence schemes, rivers and navigation channels. The guide offers a range of solutions including the use of grass, describing the properties of grass, criteria for selection, its applicability and advantages and disadvantages compared with other types of protection.

Methodology

Much of the guidance draws from the work by Schiechtl and Stern (1997) – see reference below – and includes guidance on vegetation establishment and management. Charts are presented for various bioengineering solutions for tidal and non tidal conditions, which depend on parameters such as bank loading, bank height, bankfull velocity and bank slope. Grass (unreinforced) is only recommended for non tidal situations and specifically (See Figure 4-5) for:

- Low bank loading (e.g. grasses, crops, footpaths, animals)
- Bank heights < 1.5m
- Bankfull velocity up to 4 m/s
- Bank slope < 34°

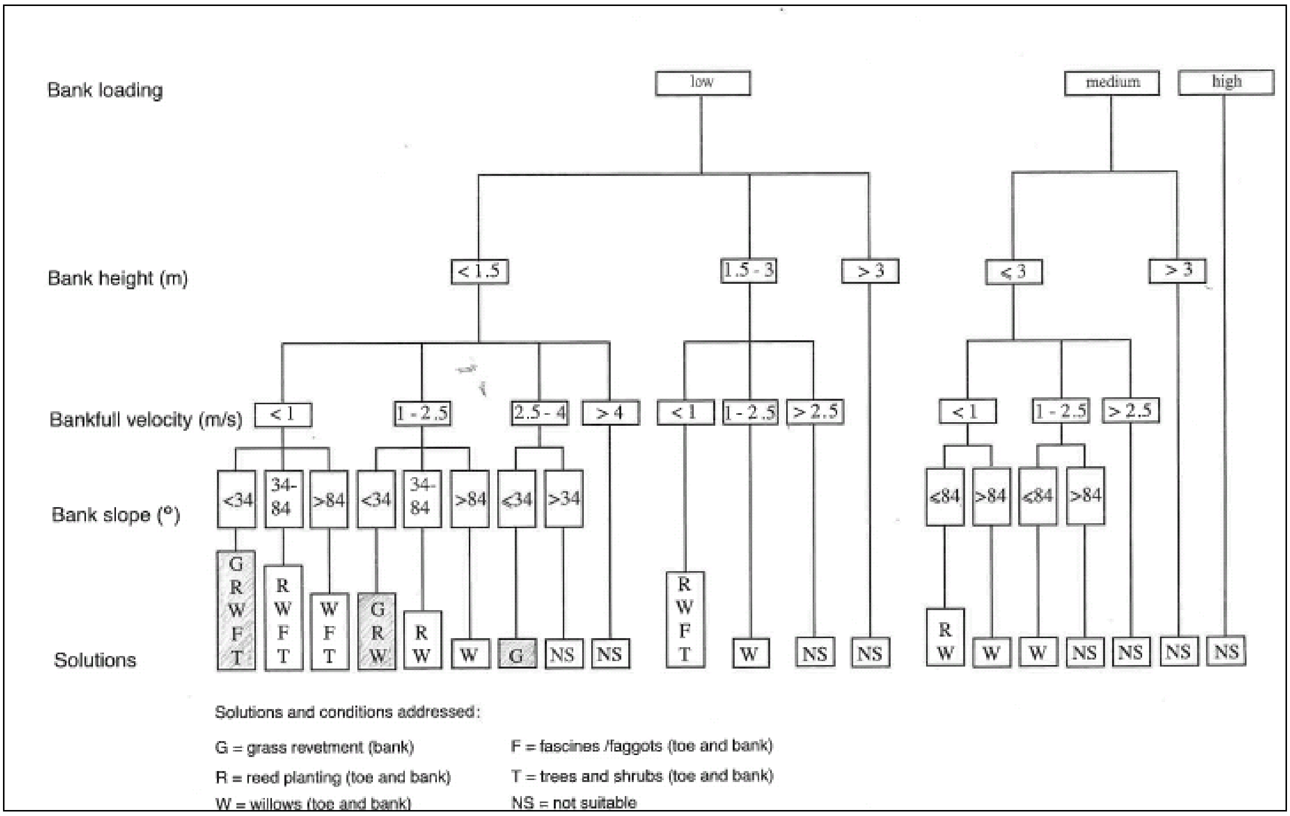


Figure 4-5: Bioengineering solutions for non tidal channels

The guide also provides recommendations for reinforced grass systems, which can be applied for

the same conditions as unreinforced but bank height up to 3m. **Advantages**: Practical guide giving simple information on the applicability of grass revetments **Disadvantages**: Guidance is based on river bank protection.		
Question	***Yes/ No***	***Comments***
Does the research provide design and / or performance guidance?	Yes	For practical application in design and site assessments
Is the research relevant to conditions in Europe? (i.e. Grass type; test conditions, etc)	Yes	Developed in the UK
Is the guidance generally applicable? (If not list specific conditions such as wave overtopping, overflow, steep slopes etc. in the comments box)	No	Applicable to river/channel situations
Could the research provide access to grass performance data? (Explain how and what data in the comments box if applicable).	No	Data used from published sources
Does the research have an ongoing programme of work? (List in the comments box if applicable)	Not known	Unlikely
Source of information / further information: Environment Agency (1999). "Waterway bank protection: a guide to erosion assessment and management", Environment Agency (Research Contractor: Cranfield University, UK, ISBN 0 11 310160 0. Schiechtl, H. M. and Stern, R. (1997). Water bioengineering techniques for watercourse bank and shoreline protection. Blackwell, Oxford.		

4.1.5 Handbook for assessment of hydraulic performance of environmental channels (2001)

Project Description:

This handbook describes the work that was carried out by HR Wallingford (HRW) in the UK to provide information that can be used to assess the hydraulic performance of environmentally acceptable channels. A number of widely known environmental features have been identified and recommended procedures for determining the hydraulic performance of them have been given with worked examples presented to illustrate these procedures.

Methodology

Chapter 3.5 of the handbook discusses vegetation performance. It presents the advantages and disadvantages of having vegetation within a channel. It also describes the different types of river vegetation and recommends a number of methods that vary in complexity to determine their impacts on the flow. For grass cover, the hand book also recommends the method described above in sections **Error! Reference source not found.** and **Error! Reference source not found.**. In this handbook, the equations developed by Green and Garton (1983) for the calculation of Manning's roughness coefficient in each of A to E retardance classes are also presented (See Table 4-2).

An extension of the above method by Kouwen, Li and Simons (1981) was also presented in this document. This method adds an additional parameter which represents the grass stiffness (k) to calculate the retardance coefficient. The reader is referred to Table 3.5.3 in the handbook for guidelines on the stiffness values for various grass types.

The handbook stated that the modified method of Kouwen, Li and Simons is the best available for calculating the flow resistance due to grass type vegetation cover provided a value for the stiffness parameter is known. If this is not the case, the original VR method should be used.

The handbook also includes a literature review of field and experimental studies to determine the hydraulic impact of vegetation. Chapter 3.8 of the handbook focuses on bank protection. It briefly describes the hard and soft types of protection.

Table 4-2: Grass cover retardance class equations

Retardance Class	Equation	Limits of VR (m^2/s)
A	$n = 0.44 - 1.62VR$	$VR < 0.1542$
	$n = 0.046 + \frac{0.0223}{VR}$	$0.1542 < VR$
B	$n = 0.403 - 3.3356VR$	$VR < 0.0535$
	$n = 0.046 + \frac{0.0096}{VR}$	$0.0535 < VR < 0.1792$
	$n = 0.0354 + \frac{0.0115}{VR}$	$0.1792 < VR$
C	$n = 0.034 + \frac{0.0046}{VR}$	$VR < 0.0833$
	$n = 0.028 + \frac{0.0051}{VR}$	$0.0833 < VR$
D	$n = 0.038 + \frac{0.002}{VR}$	$VR < 0.100$
	$n = 0.03 + \frac{0.0028}{VR}$	$0.100 < VR$
E	$n = 0.029 + \frac{0.0007}{VR}$	$VR < 0.123$
	$n = 0.0225 + \frac{0.0015}{VR}$	$0.123 < VR$

Advantages: Relevant information to calculate the friction coefficient of grass.

Disadvantages: Focus is on vegetation in channels rather then grass protection on embankments.

Question	***Yes / No***	***Comments***
Does the research provide design and / or performance guidance?	Yes	Provides a compilation of available methods to estimate the friction resistance of grass.
Is the research relevant to conditions in Europe? (i.e. Grass type; test conditions, etc)	Yes	UK conditions.
Is the guidance generally applicable? (If not list specific conditions such as wave overtopping, overflow, steep	No	Estimation of grass flow resistance only for current flows. This is needed to calculate the hydraulic parameters such as water depth and velocity which can

slopes etc. in the comments box)		be used to measure the grass performance.
Could the research provide access to grass performance data? (Explain how and what data in the comments box if applicable).	No	
Does the research have an ongoing programme of work? (List in the comments box if applicable)	No	

Source of information / further information:

Fisher, K. R. (2001). Handbook for assessment of hydraulic performance of environmental channels. HR Wallingford (SR490).

Green, J. E. P. and Garton, J.E. (1983). Vegetation lined channel design procedures. Trans ASAE. Vol 26(2).

Kouwen, N., Li, R.M., Simons, D.B. (1981). Flow resistance in vegetated waterways. Trans ASAE. Vol. 24(3).

4.1.6 Urban river basin enhancement methods project, Urbem (2002-2005)

Project Description:

The Urban River Basin Enhancement Methods (URBEM) project was funded by the EC under the 5th Framework to provide new tools, techniques and procedures to enhance watercourses located in urban areas across Europe. URBEM aimed to provide, for those who are involved in urban river rehabilitation, the best and most innovative practice that can be used in developing a comprehensive rehabilitation scheme to achieve the "maximum ecological potential" requirements of the European Union (EU) Water Framework Directive.

Methodology

URBEM was divided into a number of work packages. The most relevant one for this work was *WP8* which aimed to develop innovative techniques for urban watercourse rehabilitation. The *WP8* report gave specifications for new materials and techniques that use bioengineering to improve stream performance including performance during flooding. Those techniques also incorporate an aesthetic aspect to improve the visual view of the river defences in urban areas. The resistance limits of these soil bioengineering methods were presented in the report and are shown in Table 4-3. These figures are either based upon investigations with an underlying hydraulic calculation or from experiences.

Table 4-3: Representative limit values of soil-bioengineering measures

Technique	*Author*	*τ [N/m²]*	*v [m/s]*	*Remarks*
Willow brush mattress	Florineth (1982)	195 – 218		$\tau = \rho g R J$ Age: 15
		256 – 298		$\tau = \rho g h J$ months
	Florineth (1995)	309*		$\tau = \rho g R J$ Age: 7
		465		$\tau = \rho g h J$ months
Wattle fence	Steiger (1918)	50		
	Gerstgraser (1998b)	100 – 120	3.2 – 3.5	
Dead Fascine	LfU (1996)	70 – 100	2.5 – 3.0	
Fascine	LfU (1996)	100 – 150	3.0 – 3.5	
Row of fascines	Gerstgraser (1998b)	150 – 200	3.3 – 3.8	
Fascine wall	Gerstgraser (1998b)	180 – 240	3.5 – 4.0	
Fascine on brush layer	Gerstgraser (1998b)	120 – 150*	2.0 – 2.5*	
Geotextile on brush layer	Gerstgraser (1998b)	120 – 160*	3.0 – 3.5*	
Geotextile with live stakes	Gerstgraser (1998b)	80 – 120*	2.2 – 2.8*	Age: 15 months
Live willow stakes	Witzig (1970)	165		
	LfU (1996)	100 – 150	3.0 – 3.5	
Willow bushes	Witzig (1970)	100		
Rows of tree stumps	Gerstgraser (1998b)	50 – 80*	1.5 – 2.0*	
Sods, lawn	Witzig (1970)	50 – (100)		Without intensive care
	Witzig (1970)	80 – 100		With intensive care, slope < 2:3
Grass seeding	LfU (1996)	40	1.8	
Sod slabs	LfU (1996)	> 60	> 3.5	
Gravel-lawn	LfU (1996)	30	1.5	

* Structures damaged or destroyed.

The report shows that hard protection provides a high level of reliability from construction onwards, with a slow decrease within the construction's lifetime, whereas soil-bioengineering methods (including grass) may reach and exceed the same level of safety after some time of intensive maintenance (see Figure 4-6).

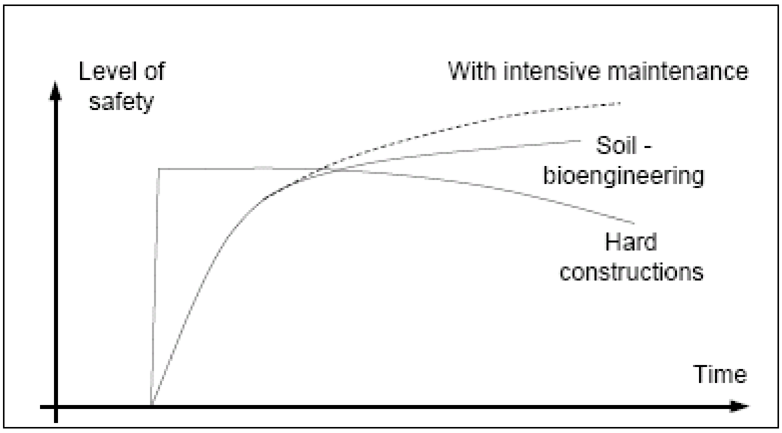


Figure 4-6: Level of safety and risk of different construction methods over time

Advantages: Provides methods for slope protection and rehabilitation in urban areas and their resistance limits. This could benefit the FloodProBE research.

Disadvantages: Focus is not primarily on grass performance.

Question	***Yes / No***	***Comments***
Does the research provide design and / or performance guidance?	Yes	URBEM provides the best and most innovative practice that can be used in developing a comprehensive rehabilitation scheme in urban areas but is limited with regard to flood embankment protection.
Is the research relevant to conditions in Europe? (i.e. Grass type; test conditions, etc)	Yes	European context.
Is the guidance generally applicable? (If not list specific conditions such as wave overtopping, overflow, steep slopes etc. in the comments box)	No	Guidance is based on river flow situations.
Could the research provide access to grass performance data? (Explain how and what data in the comments box if applicable).	No	
Does the research have an ongoing programme of work? (List in the comments box if applicable)	No	

Source of information / further information:

http://www.urbem.net/index.html

Faber, R., (2004). New techniques for urban river rehabilitation, URBEM, Work Package 8.

4.1.7 Reducing uncertainty in river flood conveyance – roughness review (2003)

Project Description:

This report was one of the outputs of a major programme of research funded jointly by the UK DEFRA/Environment Agency aimed at obtaining better predictions of flood water levels, and hence reduced flood risk. A new Conveyance Estimator System (CES) was developed which included a Roughness Estimator. To inform this estimator, a roughness review document was compiled describing the various methods and techniques of estimating roughness available. The work considered the hydraulic roughness resulting from various sources (e.g. river bed, floodplain crops and woody vegetation, in-channel vegetation) including grass on banks and floodplains. These are relevant for the current assessment. The sources of information/data relevant to grass cover not described elsewhere in the present report are summarised below.

Methodology – literature review

Ree, Wimberly and Crow (1977)

Manning's n values for the overland flow surfaces of a grassed watershed were derived by hydrograph analysis and by using average watershed slope and overland flow length values determined by geomorphic methods. These values were compared with Manning n values from laboratory tests on channels having similar grass covers. Close agreement was found for poor grass but not for fair and good grass cover. The table below gives values for three watersheds with three cover conditions.

Table 4-4: Manning's n values for grassed watersheds

Cover condition	Watershed		
	W1	W3	W4
Good	0.21	0.31	0.62
Fair	0.35	0.31	0.51
Poor	0.26	0.28	0.25

Weltz, Arslan and Lane (1992)

In this study data were collected from 14 different native rangeland areas in the western United States. Hydraulic roughness coefficients were calculated for surfaces ranging from smooth bare soil to gravely bare soil and sparsely to densely vegetated rangeland areas. A table of "effective roughness" coefficients (and their ranges) for grass is presented below together with an indication of the biomass.

Table 4-5: Range of Manning's n values for rangeland areas in western United States

Soil texture/vegetation type	Standing biomass (kg/ha)	Manning's n roughness value	Range
Native grasslands, desert	750	0.64	-
Native grasslands, shortgrass prairie	620	0.42	0.15-0.73
Native grasslands, shortgrass prairie	-	0.15	0.1-0.2
Native grasslands, mixedgrass prairie	1,620	0.52	0.31-0.78
Native grasslands, tallgrass prairie	3,080	0.79	0.16-0.97
Native grasslands, tallgrass prairie (burned)	-	0.23	0.19-0.29
Pasture, Bermuda grass	-	0.41	0.3-0.48
Pasture, bluegrass sod	-	0.45	0.39-0.65
Grassed waterways, tallgrasses		0.6	0.45-0.75

Technology Research Centre Japan (1994)

The Technology Research Centre in Japan presents a relationship for different types of grass where the roughness is a function of the relative water depth (h) and grass height (h_v). The values can be used as an alternative to the SCS method when the product VR is difficult to estimate. The values are given in the following table:

Table 4-6: Alternative values of roughness for grass

Description	Manning's n roughness values		
	Average	Lower	Upper
Stiff grass height hv= 1.8m h/hv=1.4	0.1	0.08	0.12
Grassland height hv=1.0m h/hv=2	0.08	0.07	0.09
Stiff grass height hv=1.8m, h/hv= 2.5	0.047	0.04	0.055
Grassland height hv = 50cm, h/hv= 5	0.04	0.035	0.045

Grassland height hv = 10-20cm, h/hv= 16	0.026	0.022	0.028
Flat golf course with turf several cm high, h/hv= 90	0.021	0.018	0.024

Advantages: Simple values of Manning's n for direct application; values obtained for floodplains which can be considered approximate to conditions in flood embankments, i.e. relatively shallow flows.

Disadvantages: The studies reported in this literature review suggested values for the hydraulic resistance of grass (Manning's n) but permissible velocities were not determined.

Question	***Yes / No***	***Comments***
Does the research provide design and / or performance guidance?	Yes	Only concerning hydraulic resistance
Is the research relevant to conditions in Europe? (i.e. Grass type; test conditions, etc)	No	Grasses reported were from American and Japanese studies
Is the guidance generally applicable? (If not list specific conditions such as wave overtopping, overflow, steep slopes etc. in the comments box)	No	Applicable to overland flow in the context of river out of bank flooding
Could the research provide access to grass performance data? (Explain how and what data in the comments box if applicable).	No	Studies are fairly old
Does the research have an ongoing programme of work? (List in the comments box if applicable)	No	As far as known

Source of information / further information:

Ree, W.O., Wimberley, F.L. and Crow, F.R. (1977). Manning 'n' and the overland flow equation. Transactions of the American Society of Agricultural Engineers 20, 89-95.

Weltz MA, Arslan AB and Lane LJ, (1992). Hydraulic roughness coefficients for native rangelands. Journal of Irrigation and Drainage, 118, 776-790.

Technology Research Center for riverfront development (1994). Proposed guidelines on the clearing and planting of trees in rivers. Japan.

4.1.8 Grassed surface water channels for road drainage (2006)

Project Description:

A long term research study (from 1998 to 2006) on the performance of grassed channels was undertaken for the UK Highways Agency by HR Wallingford (HRW) in association with TRL Ltd (formerly the Transport Research Laboratory) and with assistance from the Sports Turf Institute (STRI). The purpose of the research was to investigate available options for grassed channels used for drainage of roads and to demonstrate the performance of the proposed system by laboratory experiments and field trials. The results of the study were compiled into an Advice Note, HA119: Grassed channels for highway runoff (HA119, DMRB 4.2), giving guidance on the use of grassed channels for road drainage. A paper on the hydraulic resistance characteristics of grassed channels was also produced (Escarameia et al, 2002 – see Source of information below).

Methodology

The investigation was conducted in various stages and covered many aspects not all relevant to flood embankments but included:

1. the identification of suitable grass types (UK native)
2. the conditions for establishment and maintenance of grass covers
3. the experimental determination of the hydraulic resistance of two types of European grass (a Perennial Ryegrass dominated mixture and a Fescues dominated mixture) subjected to shallow current flows
4. development of resistance equations
5. full scale site trials using a turf mix consisting of 60% Fescues and 40% Bent and monitoring of rainfall and runoff depth in the grass channels as well as permeability, grass quality and growth, and water quality
6. development of numerical model based on kinematic wave theory and the design equations and comparison with field data
7. development of design guidance.

<u>Hydraulic resistance formulae:</u>

The experimental study using two types of grass that are common in the UK found a dependence of Manning's n on the grass height as well as on the product VR, as follows:

Manning's equation:

$$Q = \frac{A}{n} R^{\frac{2}{3}} \; S^{\frac{1}{2}} \qquad \text{(X1)}$$

where

A is the cross-sectional area of the channel (m^2)

R is the hydraulic radius (m)

S is the slope of the channel

$$n = 0.05 + 0.0048\ (1 + \alpha)\ \frac{H}{VR}$$

where

α = 0 for Perennial Ryegrass (valid for $0.0017 \leq VR \leq 0.0495 m^2/s$ and $0.040m \leq H \leq 0.060m$)

α = 1 for Fescues (valid for $0.0029 \leq VR \leq 0.029 m^2/s$ and $0.040m \leq H \leq 0.150m$)

V is mean flow velocity (m/s)

R is hydraulic radius (m).

For Perennial Ryegrass with height above 0.150m (and up to 0.400m), it was suggested to take n as 0.5. The above design equation is valid for fully established grass and water depths up to 0.2m.

Grass establishment and growth:

The study identified the two most viable methods of lining channels with grass as hydroseeding and turfing; but turfing allowed faster establishment.

In the tests the two native grass types used were supplied as turf in June 1999. Both grass types mixes (Perennial Ryegrass and Fescues) established equally well and easily, aided by regular watering and by mowing to keep the grass to a height of about 40mm (this helps keep a dense grass cover). The establishment was fully achieved in 3 to 4 weeks. The Perennial Ryegrass was found to be more vigorous than the Fescues, growing to average heights of 400mm, compared to a maximum of about 65mm for the Fescues. For the particular conditions of the test facility, the Fescues test channel appeared also to be more prone to infestation by weeds and other grass types and more sensitive to lack of water. The frequency of mowing depended on the grass type, with the Perennial Ryegrass requiring higher frequency than Fescues dominated mixtures. For this reason, Fescues appeared to be more suitable as they minimised maintenance requirements. After establishment, the study recommended that a minimum of two cuttings be carried out during the growing season (between May and September) and one at the start of the following growing season.

Infiltration rates/permeability:

Infiltration rates through the grass are dependent on the soil type and climatic conditions as well as flow rates and water depths. For the conditions of the hydraulic tests, infiltration rates were found to be typically less than 0.008 l/s per m^2 of channel. Permeability tests undertaken during the field trials during different seasons at a number of locations indicated very variable permeability depending on precedent weather conditions, ranging from 0.001m/s to 0.33m/s.

Advantages: The study was specifically aimed at shallow flows (up to 200mm depth) such as those likely to occur over embankments, but within a channel context. Native European grasses were studied both experimentally and in field trials which produced information of grass establishment and maintenance requirements.

Disadvantages: The study developed formulae for the hydraulic resistance of grass only (Manning's n); i.e. permissible velocities were not determined.

Question	***Yes / No***	***Comments***
Does the research provide design and / or performance guidance?	Yes	Provides design formulae for the hydraulic resistance of two types of native European (UK) grasses in a shallow (up to 200mm of flow depth) channel conditions.
Is the research relevant to conditions in Europe? (i.e. Grass type; test conditions, etc)	Yes	Two different UK grass mixtures were studied (Perennial Ryegrass dominated mixture and Fescues dominated mixture); experimental tests and site trials were performed in the UK
Is the guidance generally applicable? (If not list specific conditions such as wave overtopping, overflow, steep slopes etc. in the comments box)	No	Design equations are for resistance of grass in shallow conveyance situations (no wave overtopping or combined wave overtopping and overflow).
Could the research provide access to grass performance data? (Explain how and what data in the comments box if applicable).	Yes	See Escarameia, M. and Todd, A.J., 2006
Does the research have an ongoing programme of work? (List in the comments box if applicable)	No	Study completed

Source of information / further information:

Escarameia, M. and Todd, A.J., 2006 “Grassed surface water channels for road drainage. Project report”, HR Wallingford Report SR662, March 2006.

HA 119 (DMRB 4.2) Grassed surface water channels for highway runoff. Volume 4, Section 2, Part 9. The Stationery Office, UK.

Escarameia, M., Gasowski, Y. and May, R., 2002 “Grassed drainage channels – hydraulic resistance characteristics”, Proceedings of the Institution of Civil Engineers, Water & Maritime Engineering 154, December 2002 Issue 4, pages 333-341.

4.1.9 Management of flood embankments (2007)

Project Description:

This UK funded project aimed to provide guidance on good practice relating to management of flood embankments focusing primarily on reducing the risk of embankment failure under extreme conditions. This guide applies to a wide range of flood defence embankments. It covers all types of fluvial and coastal embankment, but does not include revetments or sea / river walls where the defence structure is predominantly constructed from rigid concrete, steel or masonry.

The guide provides a framework for the management of flood defences that includes condition and performance assessments. Part of the guide also focuses on the vegetated embankments, the factors that can affect their performance and implications for management and maintenance. The guide was mainly developed for the UK but it can also be used for applications in Europe.

Methodology

The aim of the guide was to present an overview of embankment performance issues. It does not offer detailed guidance on specific methods and practice, but rather a compendium of good practice with reference to existing guidance wherever possible. The CIRIA 116 guide is one of the references offered for a method to estimate grass cover performance.

Advantages :

N/A - reference

Disadvantages:

N/A – reference

Question	***Yes / No***	***Comments***
Does the research provide design and / or performance guidance?	No	
Is the research relevant to conditions in Europe? (i.e. Grass type; test conditions, etc)	Yes	UK conditions
Is the guidance generally applicable? (If not list specific conditions such as wave overtopping, overflow, steep slopes etc. in the comments box)	Yes	
Could the research provide access to grass performance data? (Explain how and what data in the comments box if	No	

applicable).		
Does the research have an ongoing programme of work? (List in the comments box if applicable)	No	
Source of information / further information: DEFRA and EA (2007). Management of Flood Embankments. A good practice review, R&D. Technical Report FD2411/TR1.		

4.1.10 Combined functions in coastal defence zones (2006-2007)

Project Description:

The COMbined functions in COASTal defence zone (ComCoast) project created and applied new methodologies to evaluate multifunctional flood defence zones from an economical and social point of view. A more gradual transition from sea to land creates benefits for a wider coastal community and environment whilst offering economically and socially sound options. The aim of ComCoast was to explore the spatial potentials for coastal defence strategies for current and future sites in the North Sea region.

Methodology

One of the new innovative technologies, that was identified, is the Smart Grass Revetment concept which aims at strengthening the present grass revetments at the crests and inners slopes of sea embankments. 'Smart' denotes a significant reinforcement of the grass revetment, a high-cost effectiveness, easy installation with minimum disturbance of the existing grass revetment, hidden presence and thus invisible, and durable. In addition, the system should have no environmental adverse impacts.

Two, potentially feasible, concepts have been identified:

1. Geogrid system, to be placed underneath the temporary lifted (thin-cut) grass layer (Figure 4-7);
2. Geocell system, to be penetrated through the existing grass revetment, without lifting it (Figure 4-8: Geocell system).

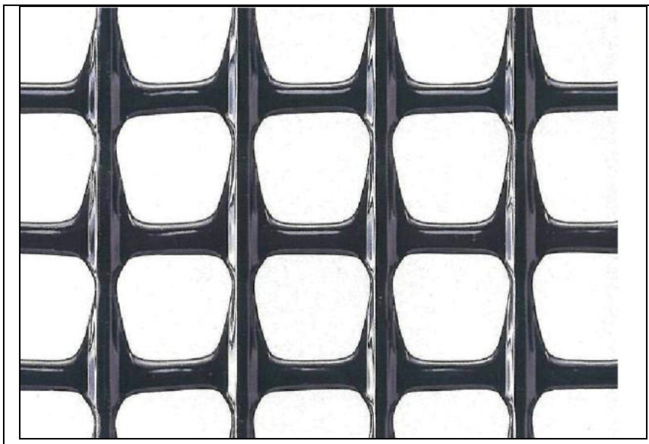


Figure 4-7: Geogrid system

Figure 4-8: Geocell system

Advantages: Provides technologies to improve the performance of existing grass protection.

Disadvantages: Focus on coastal defences and no design formulae or quantitative guidance.

Question	***Yes / No***	***Comments***
Does the research provide design and / or performance guidance?	Yes	Limited to guidance on application of geogrids and geocell system; no quantitative guidance on performance
Is the research relevant to conditions in Europe? (i.e. Grass type; test conditions, etc)	Yes	
Is the guidance generally applicable? (If not list specific conditions such as wave overtopping, overflow, steep slopes etc. in the comments box)	No	Coastal defences and wave overtopping
Could the research provide access to grass performance data? (Explain how and what data in the comments box if applicable).	Yes	Pilot schemes data
Does the research have an ongoing programme of work? (List in the comments box if applicable)	No	
Source of information / further information: http://www.comcoast.org/ ComCoast WP 3, (2005), Development of Alternative Overtopping-Resistant Sea Defences, Final report.		

4.1.11 SBW project – Erosion strength of inner slopes of dikes against wave overtopping using the overtopping simulator (2007-2008)

Project Description:

The SBW is the overall research project of the Rijkswaterstaat - Waterdienst on "Strength of and Loads on Water Defence Assets". Within the project, destructive testing has been undertaken using the Wave Overtopping Simulator on real dikes to give preliminary conclusions on strength of grassed inner slopes of dikes against wave overtopping.

Methodology:

The wave overtopping simulator (see Figure 4-9) is a device which is able to simulate overtopping waves at the crest and at the inner slope of a dike, levee or embankment in situ. The idea behind the wave overtopping simulator is that the wave overtopping can be reproduced well without reproduction of the waves at the seaside of the dike. The simulator is a box which is filled with a constant discharge of water and it then releases this water at specific times, creating an overtopping wave. The overtopping discharges could be varied within a wide range: from 0.1 l/s per m to about 50 l/s per m, the latter overtopping discharge being far beyond present overtopping standards. The device was used for the first time in the European ComCoast and Dutch SBW projects.

Figure 4-9: The wave overtopping simulator

Wave overtopping tests were performed at the end of the winters in 2007-2009. Tests were performed in the winter season, when the grass condition was in its worst state. A short description of the locations tested with some characteristics per location and per test section is given below with maximum mean discharge performed for each section.

Delfzijl, Groningen (homogeneous clay dike)

1. Normal grass cover; 50 l/s per m

2. Reinforced grass cover (geotextile; Smart Grass Reinforcement(SGR)); 50 l/s per m

3. Bare clay (20 cm of grass cover removed). 10 l/s per m

Boonweg, Friesland (60 cm clay at inner slope on top of a sand core)

1. Normal way of maintenance (grazing sheep, 4 times per year); 75 l/s per m

2. 2 times grazing sheep, no fertilizer; 75 l/s per m

3. 1 time grazing sheep, 1 time mowing/hay, no fertilizer; 75 l/s per m

4. 2 times mowing/hay, no fertilizer, no grazing/sheep. 75 l/s per m

St Philipsland, Zeeland (60 cm clay on sand core)

1. 1 time mowing/hay; steep inner slope (1:2,5), bad grass coverage. 50 l/s per m

Kattendijke, Zeeland (60 cm clay on sand)

1. 1 time mowing/hay; bad grass coverage, many moles; 75 l/s per m

2. Damage by manure injector; 2 poles in the slope; 50 l/s per m

3. Elastocoast (gravel and two-component glue); 125 l/s per m

4. Open asphalt concrete. 125 l/s per m

The testing showed that:

1. A tested inner slope of a dike, covered with grass on clay, never failed by erosion due to overtopping for a mean overtopping discharge of 30 l/s per m or less.
2. Failure only occurred at 50 l/s per m and 75 l/s per m.
3. Large erosion resistance of the inner slope of a dike is determined by the combination of grass and clay.

4. The grass cover or mattress seems stronger (Boonweg testing) if it grows on a sandy clay. Such a grass cover may resist even up to 75 l/s per m, but if significant damage occurs, the clay layer is not very erosion resistant
5. Good quality clay does not produce a very strong grass cover (it is difficult for roots to penetrate into the clay) and the grass may be ripped off for overtopping discharges around 30 l/s per m. But in that case the remaining good quality clay layer, still reinforced with some roots, has a large erosion resistance against overtopping waves.
6. A good grass cover on a sandy clay and a worse grass cover on good clay show different failure mechanisms, but they show more or less similar strength against wave overtopping. The variability of the grass sod may, therefore, have less influence on the total strength than previously anticipated. This could lead to the conclusion that the way of maintenance of the grass has only minor effect on the strength of the inner slope.
7. Transitions from slope to horizontal are probably the most critical locations for initial and
8. increasing damage. During the tests this was often the transition from the inner slope to the toe of the dike, with or without a maintenance road. Damage was initiated by a mean discharge of 10 l/s per m or more. As the damage occurred at the lowest part of the inner slope it will take time for damage to extend to the crest level and subsequently cause a dike breach. Transitions higher on the inner slope (cycle paths, stability or piping berms with or without maintenance road, tracks of tractors, roads crossing the dike), which have not yet been investigated, might be more critical. Further investigation may give more confirmative conclusions.

Based on the above testing, it was recommended, for the situation in the Netherlands, to increase the tolerable overtopping for safety assessment to 5-10 l/s per m from 0.1-1 l/s per m. But it is not recommended to increase this further.

Advantages : Provides grass performance results for different types of grass under various overtopping conditions

Disadvantages: Focus is on overtopping only

Question	***Yes / No***	***Comments***
Does the research provide design and / or performance guidance?	Yes	Provides grass performance (erosion resistance) results for different types of grass under various overtopping conditions.
Is the research relevant to conditions in Europe? (i.e. Grass type; test conditions, etc)	Yes	Mainly the Netherlands

Is the guidance generally applicable? (If not list specific conditions such as wave overtopping, overflow, steep slopes etc. in the comments box)	No	Focus is on wave overtopping
Could the research provide access to grass performance data? (Explain how and what data in the comments box if applicable).	Yes	
Does the research have an ongoing programme of work? (List in the comments box if applicable)	Yes	Further testing has been done in 2009 and 2010 (See references section).

Source of information / further information:

Steendam, G.J., J.W. van der Meer, B. Hardeman and A. van Hoven (2010). Destructive wave overtopping tests on grass covered landward slopes of dikes and transitions to berms. ASCE, Proc. ICCE 2010, Shanghai, China.

Van der Meer, J.W., Snijders, W., and Regeling, E., (2006). The wave overtopping simulator. ASCE, proc. ICCE, San Diego.

Van der Meer, J.W., (2007). Design, construction, calibration and use of the wave overtopping simulator. Comcoast, Workpackage 3: Development of Alternative Overtopping – Resistant Sea Defences, Phase 3.

Van der Meer, J.W., Steendam, G.J., de Raat, G.and Bernardini., P., (2008) Further developments on the wave overtopping simulator. ASCE, Proc. ICCE, Hamburg.

Van der Meer, J.W., Schrijver, R., Hardeman, B., Van Hoven, A., Verheij, H., Steendam, G.J., 2009. Guidance on erosion resistance of inner slopes of dikes from three years of testing with the Wave Overtopping Simulator. Proc. ICE, Breakwaters, Marine Structures and Coastlines; Edinburgh, UK.

Wave Overtopping Simulator tests in Viet Nam - Two years of testing, Hai Phong and Nam Dinh province. Technical report, 2010. Project “Technical Assistance for Sea Dike Research”. Water Resources University, Ha Noi, Viet Nam.

Van der Meer, J.W., B. Hardeman, G.J. Steendam, H. Schüttrumpf and H. Verheij, 2010, Flow depths and velocities at crest and landward slope of a dike, in theory and with the wave overtopping simulator. Proceedings International Conference on Coastal Engineering. ASCE. Shanghai.

4.1.12 EroGRASS (2008-2009)

Project Description:

The main objectives of the EroGRASS research project were to perform large scale model tests to investigate the failure of grass cover layers due to:

- wave impact,
- wave run-up and run-down flow and
- wave overtopping.

This project dealt with the investigation of grass cover failure along the entire dike profile: seaward slope, dike crest and shoreward slope. Large scale model tests at a dike model were performed in the Large Wave Flume of the Coastal Research Centre – a joint centre of the University of Hanover and the Technical University of Braunschweig in Germany. The design, construction and experimental procedure of the large scale model tests were jointly performed by the FLOODsite Project and the EroGRASS Project.

The dike model represented a typical sea dike that is comparable to typical cross sections of sea dikes built in The Netherlands, Germany and Denmark. The test programme was divided into two phases. In the first phase the initiation of grass erosion on the seaward slope due to wave impact and wave run-up and run-down flow was studied. In the second phase the initiation of grass erosion on the landward slope due to wave overtopping was investigated.

Advantages :

Disadvantages:

Question	***Yes / No***	***Comments***
Does the research provide design and / or performance guidance?	Yes	
Is the research relevant to conditions in Europe? (i.e. Grass type; test conditions, etc)	Yes	
Is the guidance generally applicable? (If not list specific conditions such as wave overtopping, overflow, steep slopes etc. in the comments box)	No	Wave overtopping
Could the research provide access to grass performance data? (Explain how	Yes	

and what data in the comments box if applicable).		
Does the research have an ongoing programme of work? (List in the comments box if applicable)	No	
Source of information / further information: Piontkowitz, T.; Verhagen, H.J.; Verheij, H.; Mai Cao, T.; Dassanayake, D.; Roelvink, D.; Zielinski, M.; Kont, A.; Ploompuu, T. (2009): EroGRASS - Failure of Grass Cover Layers at Seaward and Shoreward Dike Slopes. Design, Construction and Experimental Procedure. EroGRASS User Group. Lemvig (Denmark), pp. 74.		

4.1.13 Establishing and maintaining vegetation on steep slopes – Phase 2 field trials (2009)

Project Description:

The objective of this research project, undertaken by Arup and STRI for the UK Highways Agency, was to investigate reasons for the lack of vegetation on steep slopes (defined as those having a gradient of 45^o or more) on road embankments/cuttings. Phase 2 of the project involved field trials to study the relationship between soil type, grass species and aspect on slopes with a gradient of 45^o. The test slopes were not subject to flowing water but conclusions from this project are relevant in terms of the conditions most suitable for grass establishment and maintenance.

Methodology

Field trials were carried out on seven different European grass species (seeds obtained from the Netherlands), growing either on clay or sandy soil on slopes of 45^o and orientated to four aspects (north, south, east and west). The trials were undertaken in West Yorkshire, UK, between October 2007 and March 2009. The grass species were:

- Perennial Ryegrass
- Strong creeping red fescue
- Tall fescue
- Velvet bent
- Browntop bent
- Creeping bent
- Smooth-stalked meadow grass.

The results are summarised below. They do not involve flow of water apart from runoff generated from rainfall on the test trays.

Grass coverage:

Grasses preformed generally better on clay soils (peak coverage of 80-90%) than on sandy soils (65-75%), possibly due to higher retention of moisture. Better coverage was found towards the bottom of the test trays. Better coverage was found on the north aspect trays than on other aspects.

Fast establishing species are: perennial ryegrass, smooth stalked meadow grass, strong creeping red fescue and browntop bent.

Erosion:

The tests confirmed that grass can be effective at preventing erosion: unseeded control trays had significant erosion, more significant on sandy soils facing south. There were no significant differences between the various species in terms of erosion protection. There was greater slippage in clay soil possibly due to weight from saturation. Although some species died back in the winter erosion was not enhanced; this was thought to be due to the roots still persisting in the ground.

Grass mixes:

Although the study was carried out on individual species, there is value in mixing various species. Creeping bent and velvet bent are not commonly used in the UK but it was recommended they be incorporated in grass mixes. Tall fescue and smooth stalked meadow grass were not recommended for mixes due to their poor performance.

Advantages: This study provided useful information on conditions for establishment and maintenance of several species of European grass, including erosion protection.

Disadvantages: Note that the report is a draft. The study did not involve the flow of water besides the runoff from natural rainfall.

Question	***Yes / No***	***Comments***
Does the research provide design and / or performance guidance?	Yes	Performance of European grass species, subjected only to runoff
Is the research relevant to conditions in Europe? (i.e. Grass type; test conditions, etc)	Yes	Seven different grass types were studied in West Yorkshire, UK
Is the guidance generally applicable? (If not list specific conditions such as wave overtopping, overflow, steep slopes etc. in the comments box)	No	The guidance is only qualitative (although measurements were taken) and limited to rainfall runoff
Could the research provide access to grass performance data? (Explain how and what data in the comments box if applicable).	Yes	Data is presented in the report (see below)
Does the research have an ongoing programme of work? (List in the comments box if applicable)	Yes	Present publication is a draft

Source of information / further information:

Highways Agency (2009). “Establishing and maintaining vegetation on steep slopes. Phase 2 Field trials – Interpretative report”, Draft 1, Ove Arup & Partners Ltd, November 2009.

Highways Agency (2007). “Establishing and maintaining vegetation on steep slopes. Phase 1 Literature review”, Arup, August 2007.

4.1.14 Flood embankment vegetation management trials (2009)

Project Description:

This UK funded project was a part of a suite of operational trials within the engineering theme of the joint Department for Environment, Food and Rural Affairs (Defra) and Environment Agency (EA) research and development programme. The work aimed at improving the understanding of the effects of vegetation management on the performance of the flood embankments, especially along lowland rivers.

The trials consisted of the selection of three sites in Lincolnshire and Cambridgeshire (Billingborough, Reach Lode and Ely Ouse). Each site was subjected to a series of management techniques over five-year period including:

- using a range of cutting frequencies (varying from none to six cuts per year);
- removal of mown arisings;
- treatment with herbicides;
- application of aquatic dredgings.

Important indicators of embankment performance such as soil strength and erosion resistance, soil macronutrients, soil moisture and organic content, floral and faunal communities were monitored to assess the effects of the different management techniques. The analysis of the data showed that vegetation management had a strong impact on bank performance. The study recommended further research into alternative maintenance techniques and grass mixes.

Advantages : Study provided prototype data on maintenance regimes for grass protected flood embankments

Disadvantages: No quantitative data

Question	***Yes / No***	***Comments***
Does the research provide design and / or performance guidance?	Yes	?
Is the research relevant to conditions in Europe? (i.e. Grass type; test conditions, etc)	Yes	
Is the guidance generally applicable? (If not list specific conditions such as wave overtopping, overflow, steep slopes etc. in the comments box)	Yes	Overflow

Could the research provide access to grass performance data? (Explain how and what data in the comments box if applicable).	Yes	
Does the research have an ongoing programme of work? (List in the comments box if applicable)	No	
Source of information / further information: Flood embankment vegetation management trials – final report (2009) - Science project SC030228/SR1 - Environment Agency.		

4.1.15 International levee handbook – scoping study (2010)

Project Description:

A report developed by an international working group consisting of organisations from Germany, France, Ireland, the Netherlands, the United Kingdom and the United States. The scoping study report gives detailed background and basis to produce the handbook. It contains a number of references on grass erodibility and vegetation that has been followed up and included in this literature.

At this stage (Sept 11) – the ILH (Chapter 3) contains extensive discussion about vegetation (both grass cover and woody vegetation) but does not provide any new methods for performance analysis.

Advantages :

Disadvantages:

Question	***Yes / No***	***Comments***
Does the research provide design and / or performance guidance?	No	
Is the research relevant to conditions in Europe? (i.e. Grass type; test conditions, etc)	Yes	
Is the guidance generally applicable? (If not list specific conditions such as wave overtopping, overflow, steep slopes etc. in the comments box)	Yes	
Could the research provide access to grass performance data? (Explain how and what data in the comments box if applicable).	No	
Does the research have an ongoing programme of work? (List in the comments box if applicable)	Yes	

Source of information / further information:

http://www.leveehandbook.net/

4.2 Region 2: The rest of the world

4.2.1 US Soil Conservation Service (1954)

Project Description:

The Soil Conservation Service (SCS, 1954) of the US Department of Agriculture (USDA) developed a method for the design of grass-lined channels based on the permissible velocity method.

Methodology

The method adopted the Manning equation as the resistance equation and established a dependency of the Manning roughness coefficient, n, on the product VR (V being the mean flow velocity and R the hydraulic radius of the channel). This method established five different retardance classes (See Table 4-4) corresponding to different levels of resistance to the flow offered by various American grasses (which are dependent on grass height and density) and a curve n-VR (See Figure 4-10) was allocated to each class. Later the curves were given numerical form by other researchers to allow easier computations (See Table 4-8).

Table 4-7: General guide to vegetal retardance categories

Condition	Average length	Category
Good	Longer than 30 in	A
	11 in to 24 in	B
	6 in to 10 in	C
	2 in to 6 in	D
	Less than 2 in	E
Fair	Longer than 30 in	B
	11 in to 24 in	C
	6 in to 10 in	D
	2 in to 6 in	D
	Less than 2 in	E

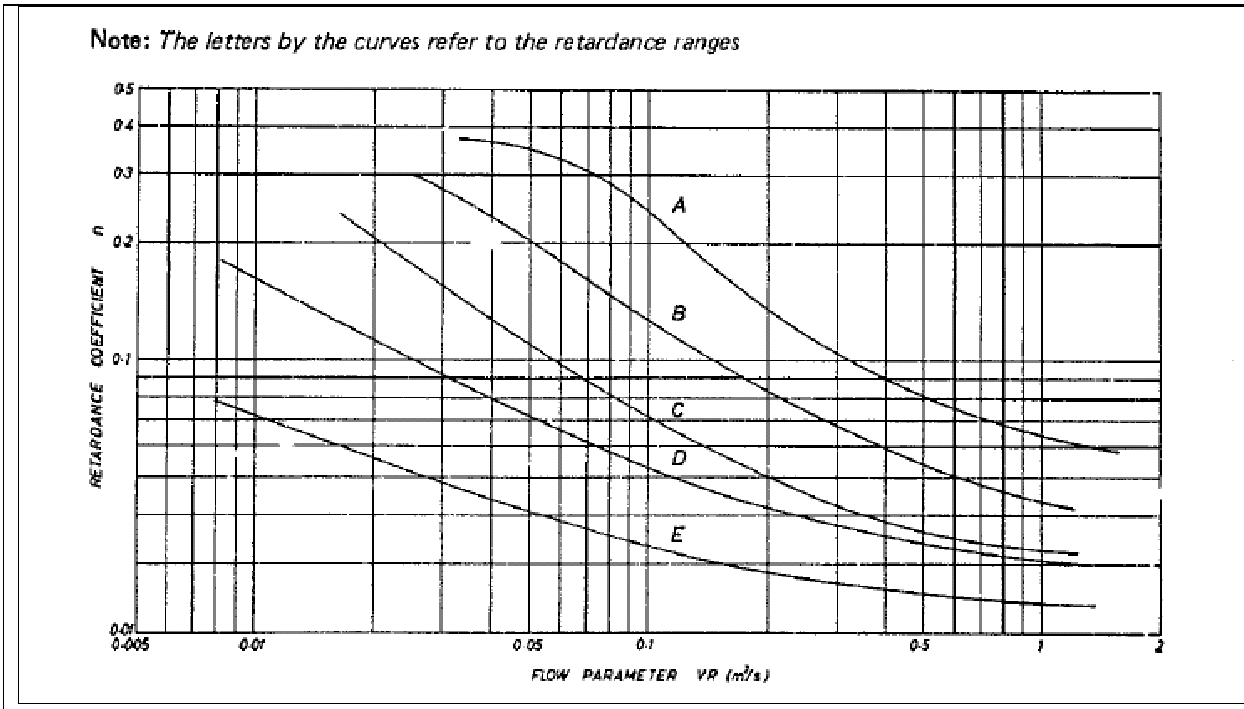


Figure 4-10: n-VR curves

Table 4-8: Grass cover retardance class equations (Green and Garton (1983))

Retardance Class	Equation	Limits of VR (m^2/s)
A	$n = 0.44 - 1.62VR$	VR < 0.1542
	$n = 0.046 + \frac{0.0223}{VR}$	0.1542 < VR
B	$n = 0.403 - 3.3356VR$	VR < 0.0535
	$n = 0.046 + \frac{0.0096}{VR}$	0.0535 < VR < 0.1792
	$n = 0.0354 + \frac{0.0115}{VR}$	0.1792 < VR
C	$n = 0.034 + \frac{0.0046}{VR}$	VR < 0.0833
	$n = 0.028 + \frac{0.0051}{VR}$	0.0833 < VR
D	$n = 0.038 + \frac{0.002}{VR}$	VR < 0.100
	$n = 0.03 + \frac{0.0028}{VR}$	0.100 < VR
E	$n = 0.029 + \frac{0.0007}{VR}$	VR < 0.123
	$n = 0.0225 + \frac{0.0015}{VR}$	0.123 < VR

Advantages: The SCS was the first method to be widely available and is the precursor of many studies.

Disadvantages: The methods are applicable to (deep) channels and relate to American grasses which can differ significantly from European grasses.

Question	***Yes / No***	***Comments***
Does the research provide design and / or performance guidance?	Yes	
Is the research relevant to conditions in Europe? (i.e. Grass type; test conditions, etc)	Yes	Although developed for American grasses and deeper channels than typically used Europe, these methods have been extensively applied in Europe due to lack of specific guidance.
Is the guidance generally applicable? (If not list specific conditions such as wave overtopping, overflow, steep slopes etc. in the comments box)	No	Suitable for flow in conveyance channels
Could the research provide access to grass performance data? (Explain how and what data in the comments box if applicable).	No	
Does the research have an ongoing programme of work? (List in the comments box if applicable)	No	

Source of information / further information:

SCS (1954). United States Soil Conservation Service “Handbook of channel design for soil and water conservation”. Publication SCS-TP61, United States Department of Agriculture National Technical Information Service, Springfield, Virginia, 1954.

Green JEP and Garton JE (1983). Vegetation lined channel design procedures. Transactions of the American Society of Agricultural Engineering, 26, 437-439.

4.2.2 Stability design of grass-lined open channels – Agriculture Handbook 667 (1987)

Project Description:

This handbook published by the US department of Agriculture (USDA) presents a design method for grass-lined channels. When published It is intended primarily to be used by engineers and technicians directly involved in planning, designing, or maintaining open channels where vegetation can be used as a lining for erosion protection.

Methodology

A design method was developed based on tractive force concepts and aimed at separating the effects of vegetation, soil type and channel configuration. The original n-VR curves (See Section **Error! Reference source not found.**) were collapsed into a single curve which expressed the dependency of the reference Manning's n on the vegetal retardance index and a modified form of the Reynolds number. The effective tractive force is compared with the allowable tractive force for the channel (variable according to the type of soil).

The effective tractive force is computed as given below:

$$\tau_e = \gamma \, y \, S \, (1- C_F) \, (n_s / n)^2$$

Where: γ is the unit weight of water.

y is the flow depth

C_F is the vegetal cover factor (values between 0.5 and 0.9 are suggested, depending on the type of vegetation as can be seen in Table 4-9)

n_s is the Manning's coefficient associated with the soil only

n is the Manning's coefficient for the whole channel.

The above design equations use SI units and are applicable to channels with good grass cover on fine grained soil and submerged grass.

Table 4-9: Vegetal cover factor

Cover group	Estimated cover factor C_F	Covers tested
Creeping grasses	0.90	Bermudagrass Centipedegrass
Sod forming grasses	0.87	Buffalograss Kentucky bluegrass Blue gramma
Bunch grasses	0.75	Weeping lovegrass Yellow bluestem
Legumes†	0.5	Alfalfa Lespedeza sericea
Annuals	0.5	Common lespedeza Sudangrass

Advantages :

Disadvantages:

Question	***Yes / No***	***Comments***
Does the research provide design and / or performance guidance?	No	
Is the research relevant to conditions in Europe? (i.e. Grass type; test conditions, etc)	Yes	
Is the guidance generally applicable? (If not list specific conditions such as	Yes	

wave overtopping, overflow, steep slopes etc. in the comments box)		
Could the research provide access to grass performance data? (Explain how and what data in the comments box if applicable).	No	
Does the research have an ongoing programme of work? (List in the comments box if applicable)	Yes	
Source of information / further information: Temple, DM (1982). “Flow retardance of submerged grass channel linings”. *Trans. ASAE*, 1982, Vol 25, pp 1300-1303. Temple DM (1983). “Design of grass-lined open channels”. *Trans. ASAE*, 1983, Vol 26, No.4, pp 1064-1069.		

4.2.3 US Federal Highways Administration (FHWA) Circular 15 (2005)

Project Description:

The Federal Highways Administration in its 3rd edition of the Hydraulic Engineering Circular 15 (or HEC 15) sets out the procedures for the design of roadside channels, including grass lined channels (US FHWA, 2005).

Methodology

The methodology adopted was based on the USDA method using the work by Kouwen and others (1969,1981) for the resistance equation which was considered to be most appropriate for shallow flows and short grasses. The FHWA method is based on the concept of maximum permissible tractive force and formulae are given for the determination of the applied shear stress. The permissible shear stress of a grass lining is considered to be determined by the grass itself and the underlying soil. For design purposes, in roadside channels hydraulic conditions are usually assumed to be uniform and steady, i.e. the energy slope is approximately equal to average channel slope. This assumption allows the use of a flow resistance equation such as Manning's to size a channel or determine the flow capacity of an existing channel:

$$Q = \frac{A}{n} R^{\frac{2}{3}} \ S^{\frac{1}{2}}$$

where

A is the cross-sectional area of the channel (m^2)

R is the hydraulic radius (m)

S is the slope of the channel.

The three main grass characteristics that influence its ability to resist erosion are: height, density and stiffness. The density-stiffness property of grass is defined by the C_s coefficient. This can be measured directly by using the so-called Fall-Board test or estimated through tables provided in this publication. The combined effect of grass stem height and density-stiffness is defined by the grass roughness coefficient, as follows:

$$C_n = \alpha C_S^{\ 0.10} \ h^{0.528}$$

where

C_n is grass roughness coefficient

C_s is density-stiffness coefficient (e.g. C_n =106 for grass in good condition, which is recommended as typical)

h is stem height (m)

α is unit conversion constant (0.35 for SI units and 0.237 for American units).

The Manning's roughness coefficient, n, is adapted to include the effect of the grass, as reflected by the C_n coefficient:

$n = C_n \ \tau_o^{-0.42}$

where

τ_o is the mean boundary shear stress (N/m^2).

The assessment of permissible shear stress is based on the fact that a grass lining moves the shear stress caused by the flow away from the soil surface, which then becomes subject to the so-called effective shear stress.

The permissible shear stress for the grass lining, τ_p, is given by

$$\tau_p = \frac{\tau_{p,soil}}{(1 - C_f)} \left(\frac{n}{n_s} \right)^2$$

where

$\tau_{p,soil}$ is the permissible soil shear stress (N/m^2); this is dependent on the soil particle size, cohesive strength and density. For non-cohesive soils, $\tau_{p,soil}$ can be estimated as $0.75D_{75}$; for cohesive soils HEC15 gives two approaches:

C_f is the grass cover factor; for a good cover, C_f can range from 0.5 to 0.9

n_s is the soil grain roughness:

ns = 0.016 for D_{75}<1.3mm

ns = 0.015 $(D_{75})^{1/6}$ for D_{75}>1.3mm

n is the grass lining roughness.

Values of τ_p of the order of 100N/m^2 have been obtained for grass covers.

Advantages: The method takes into account the grass cover characteristics and soil characteristics and allows both the determination of hydraulic and erosion resistance.

Disadvantages: Method developed for channels. A few parameters are not always available and therefore for practical use some assumptions are needed.

Question	Yes / No	Comments
Does the research provide design and / or performance guidance?	Yes	Both hydraulic resistance and erosion resistance can be determined
Is the research relevant to conditions in Europe? (i.e. Grass type; test conditions, etc)	Yes	Although developed for American grasses and deeper channels than typically used Europe, these methods have been applied in Europe due to lack of specific guidance.
Is the guidance generally applicable? (If not list specific conditions such as wave overtopping, overflow, steep slopes etc. in the comments box)	No	Suitable for flow in conveyance channels
Could the research provide access to grass performance data? (Explain how and what data in the comments box if applicable).	Not known	There is little value in using actual data as these are not European orientated
Does the research have an ongoing programme of work? (List in the comments box if applicable)	Not known	
Source of information / further information: Federal Highway Administration (2005). Design of Roadside Channels with Flexible Linings, HEC 15, Third Edition, USA		

4.2.4 Floodway design guide – Western Australia (2006)

Project Description:		
This Australian publication provides guidance for the hydraulic and engineering design of floodways, which are defined as roadways across a shallow depression specifically designed to overtop. According to this definition, there are parallels between floodways and flood embankments. ***Methodology*** The methodology suggests the determination of flow discharge over the floodway using the formula for broad crested weirs and of the flow velocity down the slope using Manning's equation. Vegetative covers are considered appropriate for low embankments and flow velocities lower than 1m/s but are not recommended as the primary erosion protection measure. **Advantages**: Guidance provides a useful "rule of thumb" for applicability of grass covers to prevent erosion in current overtopping situations **Disadvantages**: Basic guidance only.		
Question	***Yes / No***	***Comments***
Does the research provide design and / or performance guidance?	Yes	Only a general recommendation for the maximum velocity to avoid erosion (1m/s)
Is the research relevant to conditions in Europe? (i.e. Grass type; test conditions, etc)	Not known	
Is the guidance generally applicable? (If not list specific conditions such as wave overtopping, overflow, steep slopes etc. in the comments box)	No	Guidance applicable to current flow overtopping only
Could the research provide access to grass performance data? (Explain how and what data in the comments box if applicable).	No	
Does the research have an ongoing programme of work? (List in the comments box if applicable)	Not known	
Source of information / further information: MRWA (2006). "Floodway Design Guide". Main Roads Western Australia. Doc. 6702-02-2230 Issue 24/4/2006, Australia		

5 Observations and conclusions from the review

The following observations can be made:

1. A review of past and ongoing initiatives has been undertaken. It can be seen that practical and detailed guidance on the performance of grass under overflow or overtopping conditions is very hard to find.

2. A lot of initiatives seem to have focused on the hydraulic resistance of grass or vegetation, rather than on the performance of grass or vegetation under different hydraulic loads. In addition, there seems to be plenty of general guidance available regarding the maintenance and use of vegetation.

3. The main sources of guidance on erosion resistance seem to be limited to the three publications below. These are also linked, in that the CIRIA 116 report builds from the earlier Technical note 71; the CIRIA report also used some of the USDA data used to develop the methods outlined in the Agricultural Handbook 667.

    1. A guide to the use of grass in hydraulic engineering practice (Whitehead, 1976). (CIRIA Technical Note 71).

    2. Design of reinforced grass waterways (Hewlett et al, 1987. CIRIA Report 116).

    3. Stability Design of Grass-Lined Open Channels – Agriculture Handbook 667 (Temple at al, 1987).

4. The three initiatives above are all based upon field and laboratory work that was undertaken during the 1970s or 1980s. Enquiries were made to see whether the original data used to develop the guidance could be accessed and reanalyzed, but in each case it was found that the studies were performed too long ago and the base data and analyses were no longer accessible.

5. It was noted that the International levee Handbook (www.leveehandbook.net) will offer a comprehensive guide on the design, construction and maintenance of levees and will include guidance on vegetation performance. However, this handbook refers to existing rather than new guidance.

Based upon these observations the following conclusions regarding the future direction of work (within this review) were made:

6. A detailed analysis of the data underlying the existing guidance (i.e. CIRIA TN71, CIRIA 116 and Handbook 667) is not possible since the original data and analyses are no longer accessible.

7. Rather than analysis of the original data, a comparison of performance of the different methods may be made if suitable performance data from the failure of a grass covered levee can be obtained.

Section 7 of this report details the analyses undertaken to compare the different methods.

6 Research into grass performance under wave overtopping

6.1 Introduction

Within the Dutch SBW program (Strength and Loads on Water defenses) research was carried out on the performance of grass cover under wave overtopping loads and wave impact loads. The research program started in 2007 and ended in 2011. The research program was commissioned by the Rijkswaterstaat to Deltares and was carried out with Van der Meer Consluting, Infram and Alterra as partners of Deltares. In a slightly adjusted framework the research on the performance of grass covers will continue until 2016. In the coming period research will specifically be aimed at the influence of objects in the grass cover, transitions from grass to hard revetments and objects and grass erosion in the wave run-up zone.

The research about vegetation performance under hydraulic loading has led to a report which is expected to be finalized in the first half of 2012. The official quality control procedure, mandatory for most technical documents for safety assessments and design of water defenses, has not yet been completed for the presented models. Hence, this summary gives the current State of Art. The observations at large-scale wave overtopping tests do however show the strengths and weaknesses of grass cover on water defenses.

The Dutch safety assessment of grass cover addresses different failure mechanisms for different zones in a dike cross section. The SBW research on grass erosion was aimed at grass cover in the wave impact zone and in the wave over topping zone. The erosion mechanisms are illustrated in Figure 6-1.

In the following sections, the nature of the grass cover will be defined (Section 6.2) followed by a summary of the SBW research results for the two failure mechanisms with a brief description of the load parameters, strength characteristics and the proposed failure model (Sections 6.3 and 6.4).

6.2 Vegetation as dike surface protection

Grass cover on dikes is cheap, erosion resistant, self-repairing and (many think) has a nice appearance. These qualities make grass a desirable cover material for dikes and it is often applied, if the circumstances allow it.

Grass cover on dikes consists mainly of grass plants, however, other vegetation types such as herbaceous plants (herbs) will be present. The presence of herbs improves the dike appearance (Figure 6-2) and will not unduly influence the erodibility of the grass cover unless the presence of herbs significantly reduces the vegetation coverage of the soil (Section 6.3). The types of vegetation present in grass cover are influenced by the grass maintenance strategy (mowing, schedules and number, making hay, grazing by sheep, applying fertilizer etc.). There are various reports available regarding the correlation between the quality of grass cover and the maintenance strategy applied. This subject will not be covered in this report.

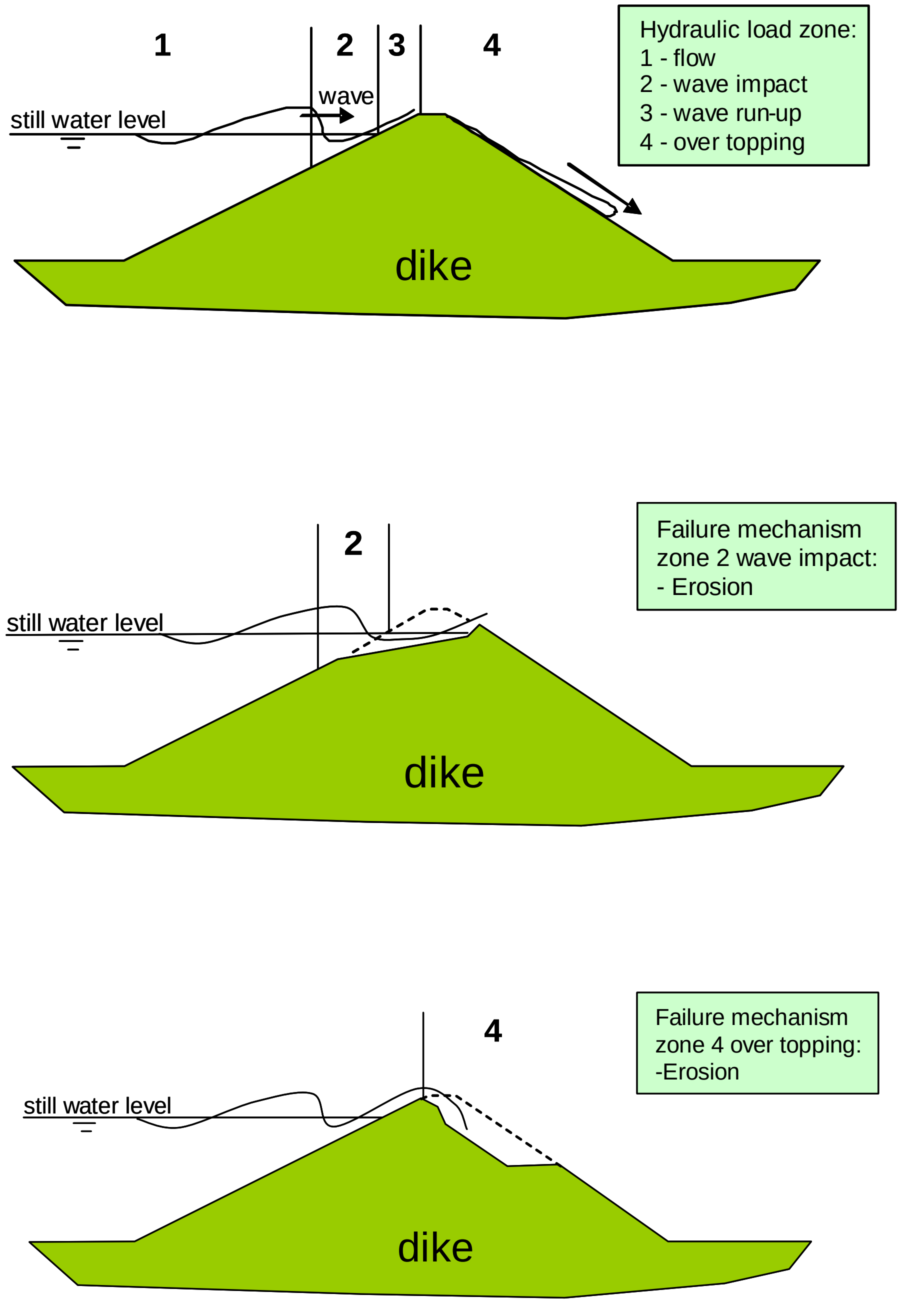


Figure 6-1: Hydraulic load zones (1 to 4) and failure mechanisms addressed in the SBW research programme

Where the grass cover is poorly maintained (rough) herbage will start to dominate, such as cow parsley, (stinging-) nettle, hogweed and Japanese knotweed (Figure 6-3). This type of vegetation will increase the erodibility of the grass cover severely and must be avoided in all dike zones where a significant hydraulic load can be expected (Sections 6.3 and 6.4). Improvement of such vegetation types is relatively easy by adjusting the maintenance strategy.

Figure 6-2: Grass cover with many species, herbs, (left) and few species (right) (TAW 1999)

Figure 6-3: Rough herbage, severe decrease in erosion resistance (TAW 1999)

A cross section showing grass cover is given in Figure 6-4. In the following sections, the performance of the lower layer is not taken into account. Failure of the grass cover is defined to be failure of the top layer, which means breach of the top layer by erosion of the cover layer as a whole. The top layer is considered to be about 0.2 m thick.

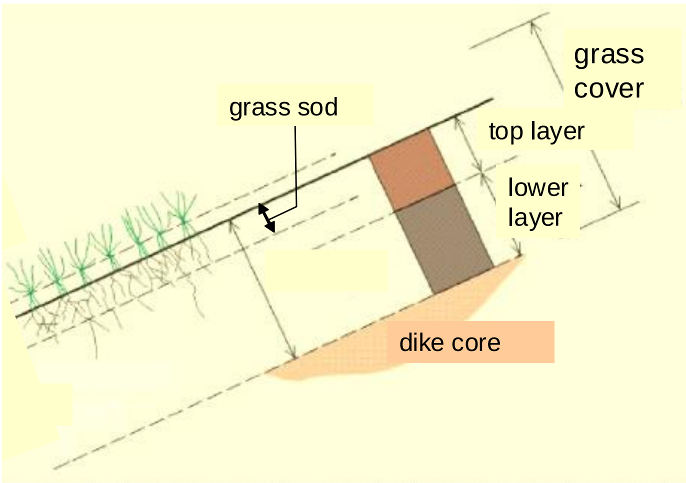


Figure 6-4: Schematic representation of the grass cover, grass sod and top layer

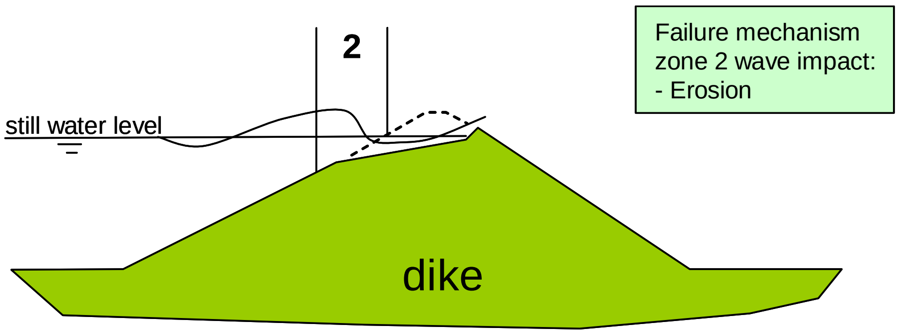
The densely rooted grass sod (around 5 cm thick) is part of the top layer. The soil underneath the sod, part of the top layer, still contains many roots and can be very resistant to erosion by overtopping water. Observation of damage development during wave-overtopping tests showed that there is a large difference between the load required to initiate damage by removal of parts of the sod and the load required to cause failure of the top layer. Even with a dike made completely of sand (sod, top layer and dike core), a distinct difference in erosion resistance was observed between grass sod, top layer and dike core.

Larger, woody vegetation such as bushes and shrubs, are not erosion resistant and must be avoided where any significant hydraulic load can be expected.

Trees growing within areas of grass cover will interfere with grass growth and will provide a focus for the hydraulic load around its trunk; they should be avoided.

The following sections describe different failure mechanisms by erosion, assuming grass cover, with the presence of herbs, but without woody vegetation such as trees, bushes, shrubs and rough herbage.

6.3 Erosion of grass cover within the wave impact zone



An investigation was made of the results of large and small-scale wave flume tests on grass covered slopes and case studies following the extreme water levels of the Rhine in 1993 and 1995, and case studies following storms from the 1970's until now along the Dutch, German and Danish Wadden- and North Sea coast. The re-evaluation has led to a model of grass cover resistance with time against wave impacts. The model is suitable for typical river dike conditions, which means a grass covered dike subject to a high water level combined with a limited wave (H_s<1 m) height caused by a storm coinciding with the high water level. Note that the design storm intensity will in general be relatively mild, because of the low probability of a large storm coinciding with an extreme water level.

6.3.1 Hydraulic load

The hydraulic load in the wave impact zone is characterized by the significant wave height H_s (m) and the wave impact loading time t_i (hour). The wave period is not explicitly included in the failure model. The wave impact erosion model, described further in this section, is based on experience from flume tests and field damage case studies for a variety of wave steepnesses, always within the range of what can be expected for typical river dike conditions, e.g. steepnesses locally generated wind-waves.

The grass cover is only subjected to wave impact loads in the range between the water level and $H_s/2$ below the water level. The loading time t_i therefore depends on the water level as a function of time and the wave height H_s as shown in Figure 5. In Figure 5 the wave loading time is given for the point on the outer slope at level A.

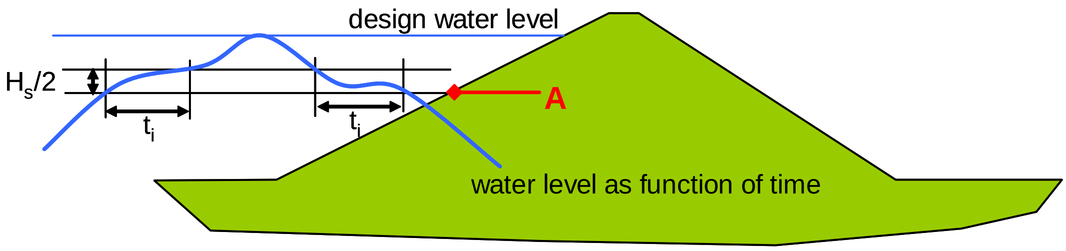


Figure 6-5: Wave impact loading time ti (hour) for level A on the slope

Note that the wave impact loading time varies along the outer slope and that the impact loading time at, and above, the design level is 0 hour.

6.3.2 Grass sod strength

Only the strength of the grass sod is considered. After failure of the grass sod, the rest of the top layer and lower clay layers (if present) will resist wave impact loading for a certain amount of time, preventing a sudden failure of the dike. The time before catastrophic failure whilst the lower layers are eroded following failure of the grass cover is not considered further here.

The strength of the grass cover greatly depends on the density of the root system in the grass sod. Open patches in the grass sod decrease the grass cover strength. A second factor of importance is the substrate soil type, however, a closed and dense root system on sandy soil is much more resistant against wave impacts than an open root system on a good quality clay, with a high plasticity index. Only where there is a fragmented grass sod (as explained in text below), the substrate soil becomes very important.

The quality of the grass sod is categorized as (decreasing strength):

Closed sod (example Figure 6-6):

- Visually continuous closed cover dominated by grass plants. Representative grass plant distance less than 10 cm and less than 10% of the grass cover has a representative plant distance of up to 20 cm.
- Less than 5 damaged patches smaller than 15 cm x 15 cm per 25 m^2.
- A peace of the sod (30 cm x 25 cm) can be taken from the cover by a shovel without falling apart. It will take some effort to tear it apart.

Figure 6-6: Examples of closed sod

<u>Open sod (examples Figure 6-7)</u>:

- Visually continuous closed cover dominated by grass plants. Representative grass plant distance less than 10 cm and less than 25% of the grass cover has a representative plant distance of up to 25 cm.
- Less than 5 damaged patches smaller than 15 cm x 15 cm per 25 m^2.
- A piece of the sod (30 cm x 25 cm) can only be taken with care from the cover by a shovel without falling apart. It takes little effort to tear it apart.

Figure 6-7: Examples of closed sod

Fragmented sod (examples Figure 6-8):

- Fragmented grass plants and patches of sod present. More than 25% of the cover has a representative plant distance more than 25 cm.
- A piece of the sod (30 cm x 25 cm) cannot be taken from the cover by a shovel, unless the soil itself has enough cohesion, is in moist condition and compacted by treading on it.


Figure 6-8: Examples of fragmented sod

With some practice, determining the grass sod quality can become a relatively simple task. Determining the sod quality must be done when the grass has recently been mowed or grazed so the representative plant distance can be easily estimated. Periodic, for instance yearly, monitoring of the grass sod quality is advised to acquire insight in the sod quality development (and incidental damages). This will enable maintenance strategy changes, if the sod development so requires.

6.3.3 Failure model

The failure model suggested for erosion in the wave impact zone compares the wave impact load time t_i (hour) with the wave impact resisting time t_r (hour) for different wave height H_s (m) as given in Figure 6-9. The grass sod is sufficiently strong if $t_r > t_i$. The model does allow some minor damage to occur to the sod.

Model limitations concerning the slope angle are 1H:2.5V (or less steep) for $H_s \geq 0.5$ m and 1V:1.5H (or less steep) for $H_s < 0.5$ m. For a slope angle more gentle than 1V:4H the resisting time t_r will increase, however, the model has no prediction capability on how much t_r will increase.

Note that a fragmented sod is not covered by the relationship shown in Figure 6-9. The strength of a fragmented sod is such that it cannot be relied upon to have enough strength to withstand any wave impacts. The strength provided by the soil beneath the sod layer is immediately relied upon.

No research within the SBW framework was aimed at erosion in the wave run up zone yet (zone 3 in Figure 6-1), however, if the grass sod present in the wave impact zone (zone 2 in Figure 6-1) is sufficient, the grass sod in the run up zone will also be sufficient. Pressure gradients in the grass sod and subsoil, causing erosion, are significantly larger in the wave impact zone then in the wave run-up zone. A grass cover will fail in the wave impact zone before it fails in the wave run-up zone, if the grass cover is of equal quality in both zones.

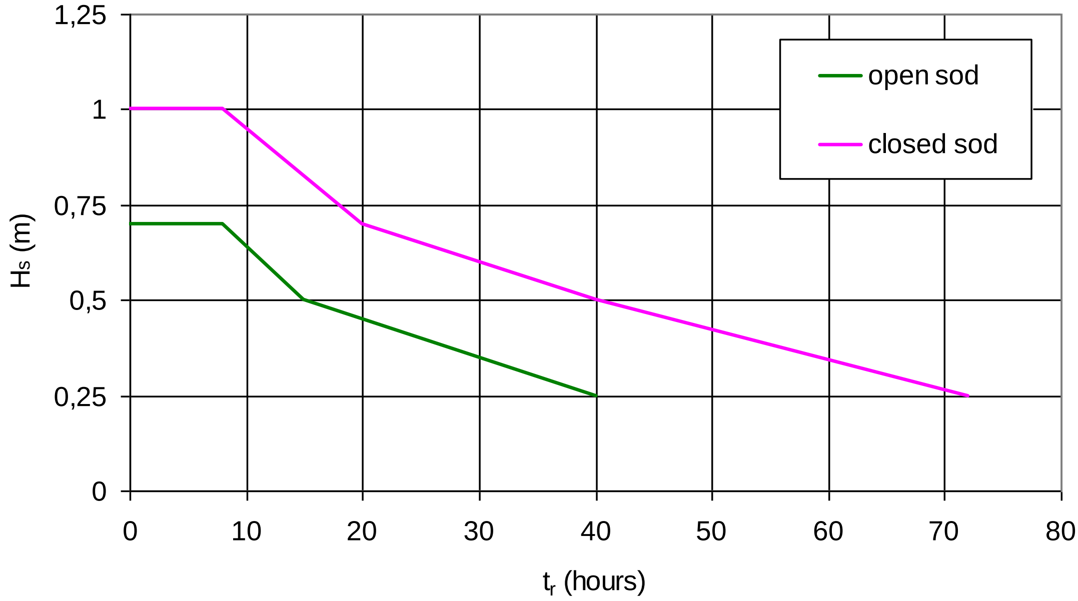
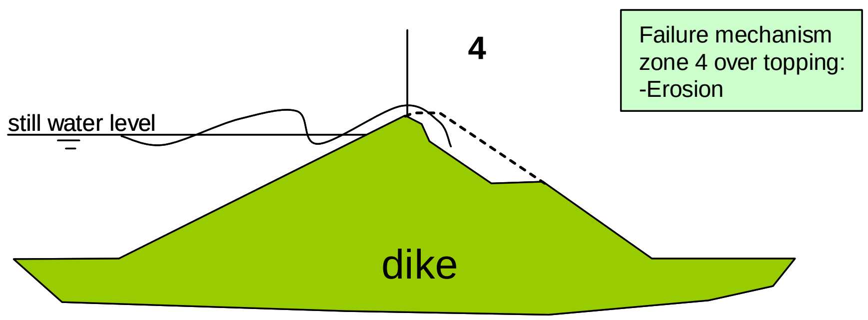


Figure 6-9: Wave impact resisting time t_r (hour) for different wave height H_s (m) and sod quality (open or closed).

6.4 Erosion of grass cover in the wave overtopping zone



Large-scale wave-overtopping tests were performed to determine the performance of grass cover under the influence of wave overtopping. More than twenty dike sections, each four meters wide, were tested to assess their performance against overtopping volumes of up to 5500 l/m. Storm conditions were simulated where the significant wave height was 2 m and the average overtopping discharge was up to 75 l/s per m. Grass cover (closed sod) proved to be very resilient against a wave overtopping load, however, some of the tests also showed situations which undermined the strength of grass cover dramatically and should be avoided if any significant overtopping is to be expected.

6.4.1 Hydraulic load

The hydraulic load for erosion of the grass cover in the wave-overtopping zone (crest and landward slope of the dike, zone 4 in Figure 6-1) consists of the overtopping wave volumes. Each of the overtopping volumes can be characterized by the maximum depth averaged flow velocity and maximum water layer thickness. As shown in Figure 6-10, each overtopping wave volume will result in a triangular shaped flow velocity development against time. The triangular shape was measured in a number of the wave overtopping tests. An example is given in.

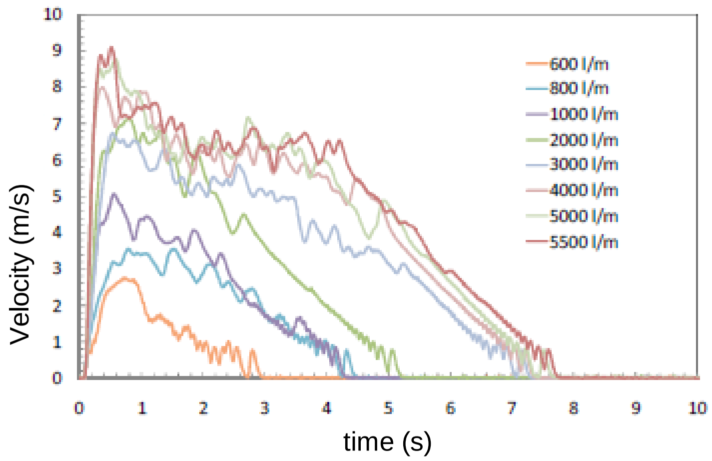


Figure 6-10: Velocity (m/s) against time (s) for different wave overtopping volumes (600 – 5500 l/m) measured at one wave-overtopping test sloped 1V:4.5H (Van der Meer et al. 2010).

The maximum depth averaged velocity U (m/s) in a wave overtopping event with a volume V (m^3/m) can be estimated by the empirical formula $U = 5*V^{0,34}$ (Van der Meer et a. 2010). For example, a wave overtopping volume of 1000 l/m results in a maximum depth averaged velocity of 5 m/s and an overtopping volume of 5500 l/m in 8,9 m/s. Measurements at a relatively steep (1V:2.3H) and long slope showed an increase in velocity as the volume progressed down slope. Measurements at a relatively mild slope (1V:5H) showed a decreasing velocity. However, until further research gives conclusive insight in the development of the velocity depending on slope angle and slope length, the above estimate of the correlation between V and U is used for slopes of 1V:2.3H and more gentle. For steeper slopes the model presented below is advised. Research to determine the velocity as a function of slope angle and slope length is in progress.

The distribution of wave overtopping volumes during a storm can be calculated using the formulae in the Overtopping Manual[1]. Parameters involved are the storm duration and the average wave period, which determine the number of waves reaching the dike. The water level, slope geometry and roughness, wave height and period, determine the number of waves that reach the crest, and overtop, and the average overtopping discharge q (l/s per m).

In engineering practice the wave overtopping load is often described by the average wave overtopping discharge only. In the examples given below the relevance of including the wave height in the overtopping load is made clear.

For example, Table 6-1 gives key parameters giving insight into the overtopping load for different wave height and overtopping discharges. The examples in Table 6-1 are given for

[1] EuroOtop, European Overtopping Manual, Wave Overtopping of Sea Defenses and Related Structures: Assessment Manual, August 2007, ISBN 978-3-8042-1064-6

- outer slope of 1V:4H,
- a wave steepness based on the peak period and deep water wave length of 0,04;
- a storm duration of 6 hours and
- an average wave period T_m equal to the peak period T_p divided by 1,2.

Table 6-1: Examples of key load parameters for different wave height H_s (m) and average overtopping discharges q (l/s per m)

		Average overtopping discharge q (l/s per m)				
		0,1	1	5	10	50
Hs = 1 m	Free board Rc (m)	2,24	1,63	1,2	1,02	0,6
	Percentage overtopping waves Pov (%)	0,7	7,2	24	35,7	70
	Number of overtopping waves Now (-)	45	471	1573	2336	4583
	Largest overtopping volume Vmax (l/m)	256	440	831	1197	3401
Hs = 2 m	Free board Rc (m)	5,06	3,84	2,98	2,61	1,76
	Percentage overtopping waves Pov (%)	0,2	2,7	11,4	18,9	47
	Number of overtopping waves Now (-)	9	126	525	867	2160
	Largest overtopping volume Vmax (l/m)	769	1222	2018	2697	6387
Hs = 3 m	Free board Rc (m)	7,98	6,16	489	4,35	3,08
	Percentage overtopping waves Pov (%)	0,085	1,49	7,05	12,3	34,9
	Number of overtopping waves Now (-)	3	55	262	456	1300
	Largest overtopping volume Vmax (l/m)	1424	2254	3478	4509	9709

An example of the wave overtopping volumes, as simulated during a wave-overtopping test, is given in Figure 6-11. The graph gives each individual overtopping volume in time (s) in the test sequence from 0,1 – 1 – 5 – 10 – 30 – 50 – 75 l/s per m for a wave height H_s of 1 m and data given in and above Table 6-1.

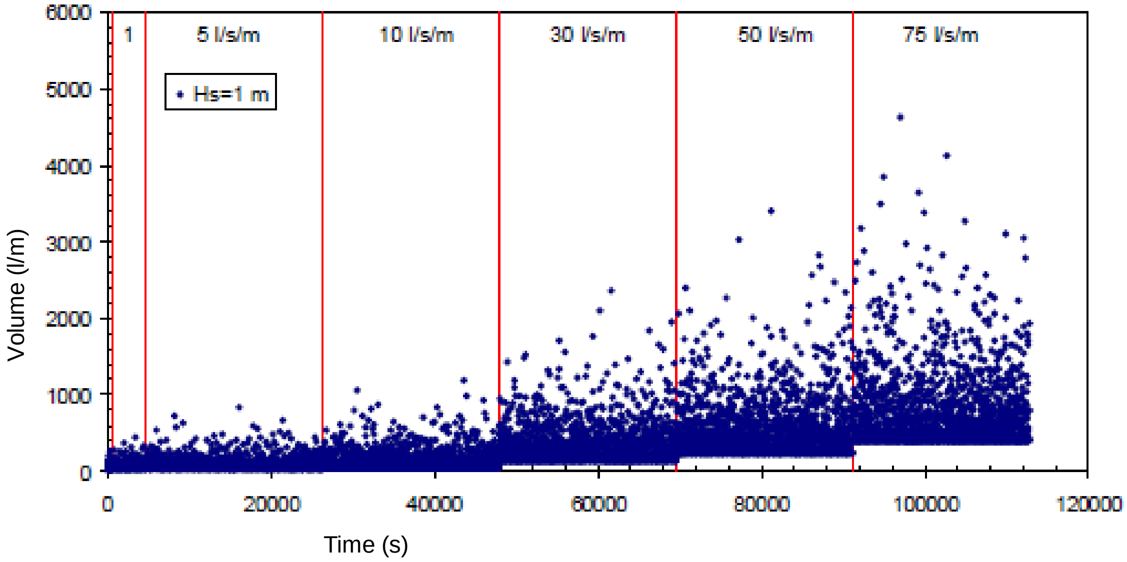


Figure 6-11: Example of the wave overtopping volumes in time, as simulated during a wave-overtopping test

The 0,1 and 1 l/s per m tests were shortened for practical reasons. The small number of overtopping volumes during the 0,1 and 1 l/s per m test, which in reality would be distributed over a 6-hour period, was condensed in a shorter period.

The example is to show and emphasize the influence of the wave height on the overtopping erosion load, and that it is not enough to just use the average overtopping discharge when describing wave over topping.

6.4.2 Strength

The strength of the grass is characterized by a critical depth average flow velocity. The critical velocity depends on the grass quality. The same factors apply as given in Section 6-2 for the strength of grass cover under wave impact loading. However, for the case of wave overtopping, it is more important to have a distinction between the grass sod and the top layer (definitions in Figure 6-4). Under wave impact loading, failure of the grass sod almost immediately results in failure of the top layer, while in case of wave overtopping, failure of the grass sod and failure of the top layer can be far apart.

The influence of small damaged spots, or small objects, in the grass sod has proved to be of little importance during the wave overtopping tests. Overtopping tests were performed on intentionally damaged slopes and on slopes with objects and damages already present. Objects and damages smaller than 0,15 m x 0,15 m did not decrease the strength much, as is taken into account in the grass sod quality (Section 6-2-2).

Larger objects and damaged spots do decrease the strength significantly, as was observed during a number of wave-overtopping tests. Unfortunately no conclusive modeling of the decrease in grass strength (and increase in load) due to these objects and damages has been developed.

6.4.3 Failure model

The suggested failure model for erosion on the crest and landward slope due to wave-overtopping is based on observations at more than twenty wave over-topping tests.

A fragmented sod does not have any strength that can be relied upon. If there is any significant wave overtopping to be expected (c.q. more than 0,1 l/s per m) a fragmented sod is not recommended..

For a closed sod, regardless of the lower layer quality, or an open sod in combination with a clay layer more than 0,4 m thick on top of a sand core (0,4 m including top and lower layer thickness Figure 4), at least 1 l/s per m will not lead to failure by erosion.

For higher overtopping discharges, extra care is needed where the clay layer is less than 0,4 m on top of a sand core (0,4 m including top and lower layer thickness Figure 4). A sand core in combination with a thin clay layer is susceptible to internal erosion and subsequent undermining of the clay layer even at low overtopping intensity. A concentrated exit of water through a mole, mouse or rabbit burrow, can easily result in sand transport from under the clay layer and lead to undermining (Figure 12).

Figure 6-12: Rapid failure because of internal erosion and undermining of the grass cover at a wave overtopping test site with a combination of fragmented grass sod and a thin clay layer

If the risk of undermining can be excluded, and if a closed sod is present, the cumulative overload model is suggested (Van der Meer et al. 2010). The model is based on the observation of damage occurrence and damage progress during more than twenty wave-overtopping tests.

The most commonly observed initial damage consisted of small patches of grass sod being removed from the cover by large overtopping volumes (example Figure 6-13).

Under some circumstances, the eroded patches can be much larger. In this case the removal is preceded by the bulging of a piece of sod, where the sod loses touch with its substrate, but is still attached to neighboring sod. A continuing large volume of flow will however, inevitably, remove the piece of sod.

The removal of pieces of sod is often first observed at the transition from the landward slope to the horizontal (i.e. at the landward toe of the dike). After the initial removal of pieces of the sod, further damage can develop.

Figure 6-13: Example of initial damage; removal of small patches of grass sod (top) and a larger piece (bottom)

After the initial damage, in most cases, the damaged spot becomes larger and forms a gully (Figure 6-14). In most cases, there are still a lot of roots, just below the grass sod, keeping the soil in place. The top layer, of which the grass sod is a part (see Figure 6-4), has not yet failed if only the grass sod is removed by erosion. The top layer fails when the erosion damage deepens below the rooted top layer, often about 0.2 m deep.

Figure 6-14: Extension of initial damage in gullies. Progress of erosion in depth was often limited and in these cases, no failure of the top layer occurred.

The wave overtopping tests show that there is not one critical overtopping volume during a storm, but that the larger volumes during a storm contribute either to the initiation of damage or to the extension of damage. Small overtopping volumes, generating depth averaged maximum flow velocities below the critical velocity, do not contribute at all. The transition between contributing overtopping volumes and volumes, which do not, is determined by a critical volume, or a critical velocity which depends on the grass quality (see Section 6-3-2).

The observations have led to the following cumulative overload model:

$$\sum_{n=1}^{n=Nov} \left(U_n^2 - U_c^2\right) < C$$ (Note in case of U_n<U_c the result is discarded)

Where,

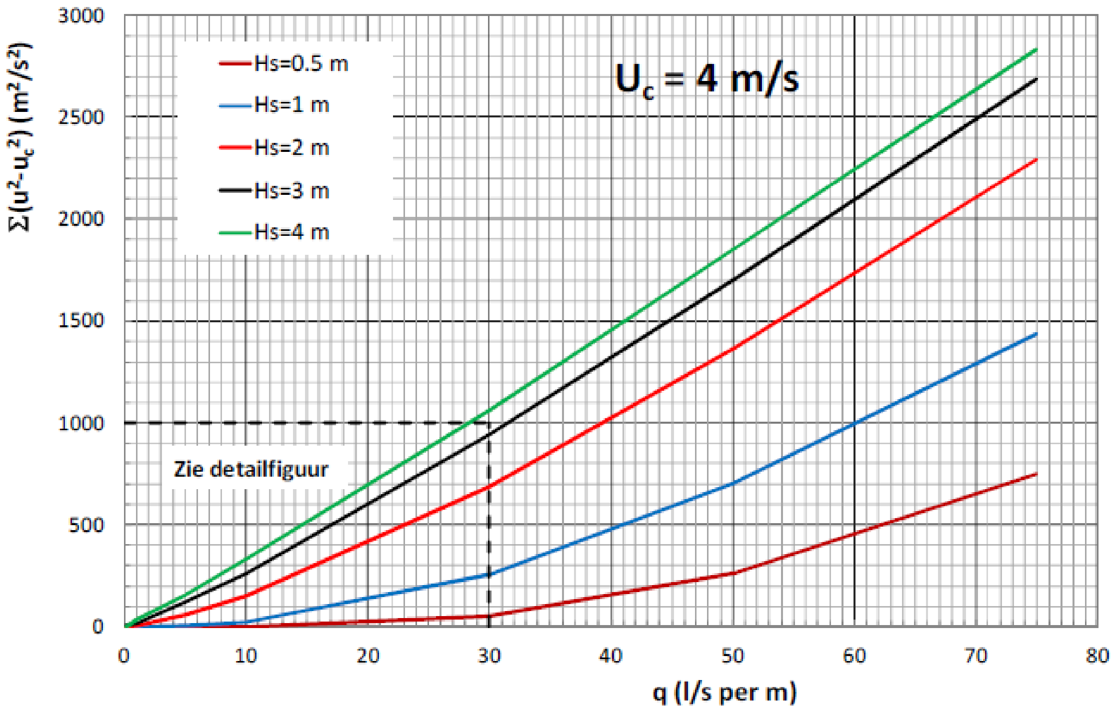
- N_{ov} number of overtopping waves.
- U (m/s) is the maximum depth averaged flow velocity from an overtopping wave, for cases where U>Uc.
- U_c (m/s) critical maximum depth averaged flow velocity depending on the top layer strength.
- C (m^2/s^2) is a critical value where:

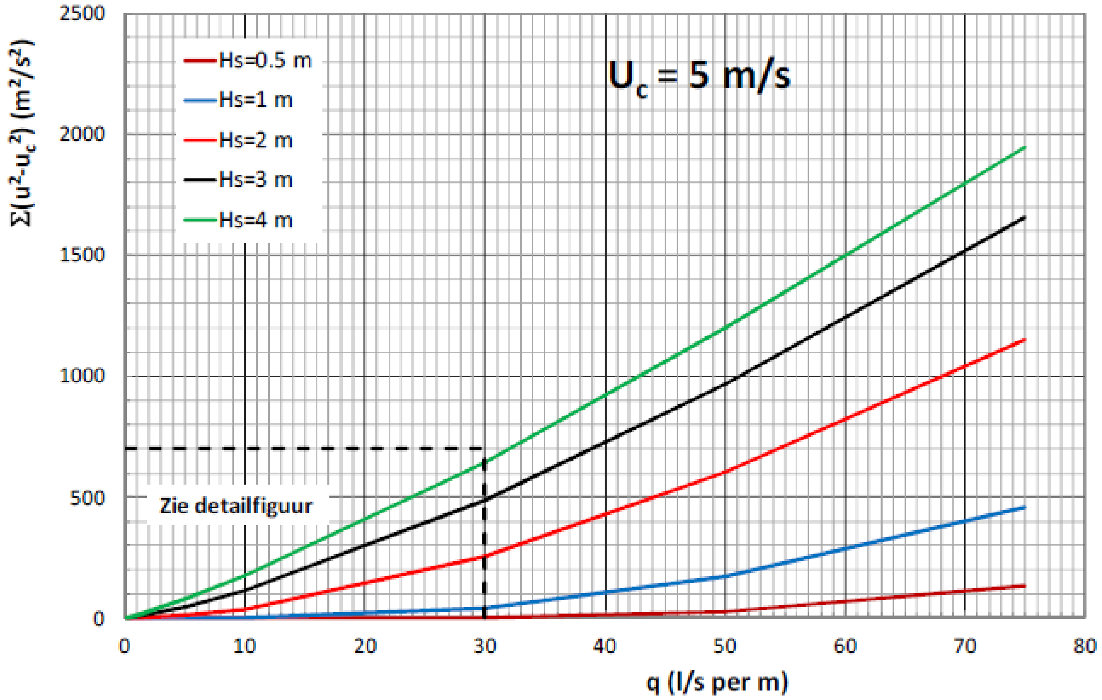
  C=500 (m^2/s^2) resembles a situation where initial damage occurs. A large scatter in the initial damage value is however observed.

  C=1000 (m^2/s^2) multiple spots with initial damage (not yet failure of the top layer)

  C=3500 (m^2/s^2) failure of the top layer.

The cumulative overload depends mainly on U_c, the storm duration, and the combination of the average overtopping discharge and the wave height H_s. From the wave overtopping tests, critical velocities were back calculated and showed a range from U_c = 4 m/s (critical volume 500 l/m) up to 6,3 m/s (critical volume 2000 l/m), excluding tests with fragmented grass sods. The cumulative overload can be compressed in the graphs given below. The graph gives (on the vertical axis) the cumulative overload for a 1-hour storm condition (Figure 6-15).





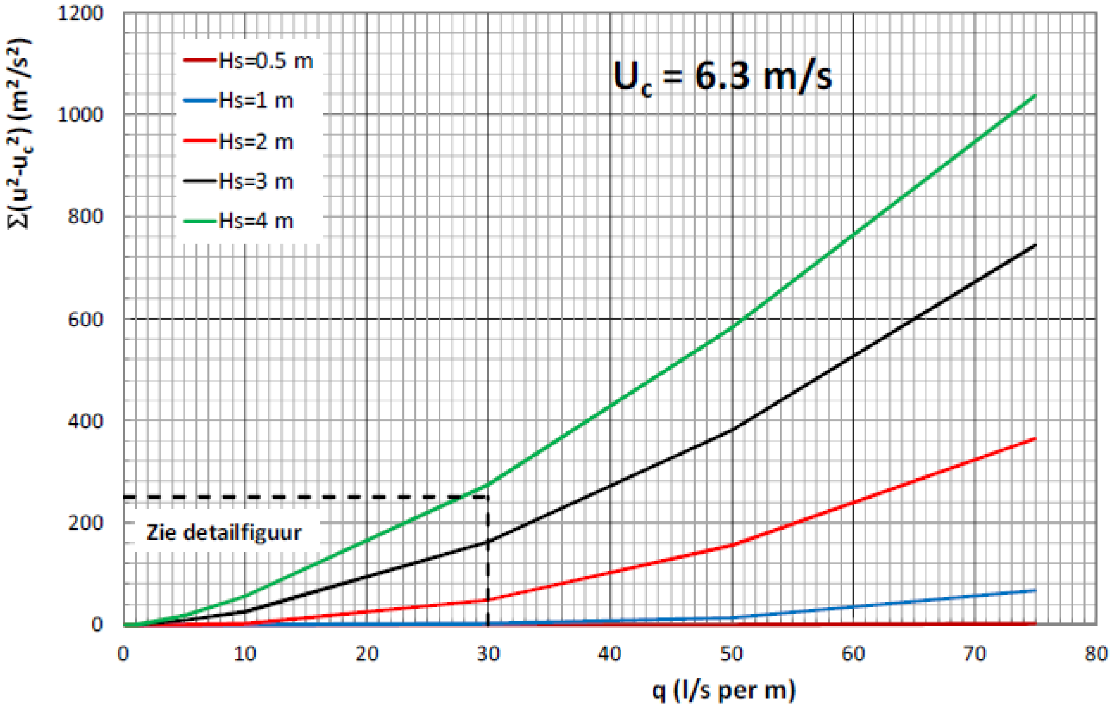


Figure 6-15: Cumulative overload (m^2/s^2) as a function of U_c (m/s), H_s (m) and q (l/s per m) for a 1 hour storm condition

The research within the SBW framework has not yet led to a reliable relation between Uc and field parameters. Based on the test results a value of U_c = 4 m/s and C= 1000 m^2/s^2 is advised for closed grass sods, and excluding cases too far beyond the range of wave overtopping tests, the most important being the slope angle of 1V:2,3H. For a closed sod it is likely that the critical velocity will be larger than 4 m/s, however, the research to predict U_c is still work in progress.

Example

For example, consider wave overtopping that lasts 6 hours, with Hs = 2 m. There are 2 hours of q = 10 l/s per m (water level rise and fall) and 4 hours of q=25 l/s per m at the peak water level. We use the graph with U_c = 4 m/s for a closed grass sod and read a cumulative overload of 150 m^2/s^2 per hour for 10 l/s per m and Hs = 2 m and 550 m^2/s^2 per hour for 25 l/s per m and Hs = 2 m. The total cumulative overload during the storm event will be 2x150 + 4x550 = 2500 m^2/s^2. This is larger than 1000 m^2/s^2, so the suggested criterion is not met.

If, in the same case U_c = 5 m/s than we read a cumulative overload of 25 m^2/s^2 per hour for 10 l/s per m and Hs = 2 m and 200 m^2/s^2 per hour for 25 l/s per m and Hs = 2 m. The total cumulative overload during the storm event will be 2x25 + 4x200 = 950 m^2/s^2. This is smaller than 1000 m^2/s^2, so the suggested criterion is met.

7 Data analysis / model testing

Based upon the review undertaken (See Sections **Error! Reference source not found.**, **Error! Reference source not found.** and **Error! Reference source not found.**), three methods have been identified to assess grass performance. These are:

Method 1: **Error! Reference source not found.** (See Section **Error! Reference source not found.**).

Method 2: **Error! Reference source not found.** (See Section **Error! Reference source not found.**).

Method 3: **Error! Reference source not found.** (See Section **Error! Reference source not found.**).

Following identification of these methods, the next step was to evaluate their capability in assessing grass performance. Test case data was sought which provided details of hydraulic load conditions as well as grass condition and the time of failure. The following sections provide a description of the test cases, modelling undertaken and analysis of the modelling results.

7.1 Test cases

Identification of test case data was not an easy task. Available data on embankment grass failure due to overflow is rare and often incomplete. The USDA data (Hanson et al 2005) was the first source for information and WP3 partners (i.e. Cemagref and Deltares) also provided data for testing. However, data from Cemagref and Deltares was eventually found to be of insufficient detail to allow for test modelling. As such, only two test cases were analysed using the USDA data.

7.1.1 Test case 1

The data of this test case comes from large-scale overtopping tests have been conducted at USDA – ARS to provide information relevant to the erosion processes of cohesive embankment breach failures. This test case was a 2.23m high and 7.32m long embankment which was constructed from silty sand soil with a grass cover. Figure 7-1 and Figure 7-2, and Table 7-1 and Table 7-2 provide description of the data for the embankment geometry and soil conditions.

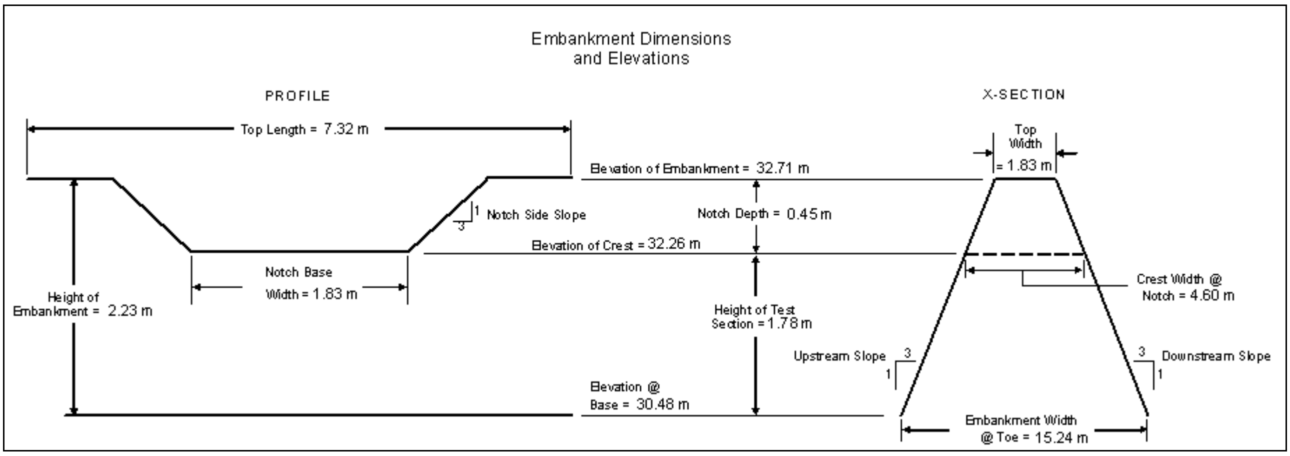


Figure 7-1: Geometry for Test Case 1

Figure 7-2: Test case 1 embankment

Table 7-1: Embankment and test section dimensions

Embankment Dimensions		Test Section Dimensions	
Height of Embankment	2.23 m	Height of Test Section	1.78 m
Elevation of Embankment	32.71 m	Notch Base width	1.83 m
Top Length	7.32 m	Notch Side Slopes	3/1 (H/V)
Top Width	1.83 m	Notch Depth	0.45 m
Upstream Slope	3/1 (H/V)	Crest Width @ Notch	4.6 m
Downstream Slope	3/1 (H/V)	Elevation of Crest @ Test Section	32.26 m
Elevation @ Base	30.48 m		
Embankment Width @ Toe	15.24 m		

Table 7-2: Embankment soil properties

Gradation		**Construction**	
% Clay < 0.002 mm	5	Compaction Effort (kN.m/m^3)	191
% Silt > 0.002 mm	25	Loose Lift Thickness	0.15 m
% Sand > 0.105 mm	70	Compacted lift thickness	0.12 m
Plasticity Index	Non-plastic	**Sieve Analysis**	% Finer
Soil Classification (USCS)	SM	0.002 mm	5
Grain Density (g/cm^3)	2.67	0.005 mm	7
Unconfined Compressive Strength (kN/m^2)	20.30	# 200 (0.075 mm)	30
Average Dry Density (g/cm^3)	1.71	# 140 (0.106 mm)	39
Average Water Content @ construction %	8.9	# 60 (0.250 mm)	71
Average Total Density (g/cm^3)	1.87	# 40 (0.425 mm)	93
Erodibility Coefficient kd (cm^3 /N.s)	10.2	# 20 (0.850 mm)	99
Critical stress □c (kN/m^2)	0.00	# 10 (2.00 mm)	100

7.1.2 Test case 2

The data of this test case also comes from the large-scale overtopping tests have been conducted at USDA – ARS to provide information relevant to the erosion processes of cohesive embankment breach failures. This test case was a 2.23 m high and 7.32 m long embankment which was constructed from clay-loam soil with grass cover. Figures **Error! Reference source not found.** and 7-4 and Tables 7-**Error! Reference source not found.** and 7-7-4 provide description data for the embankment geometry and soil conditions.

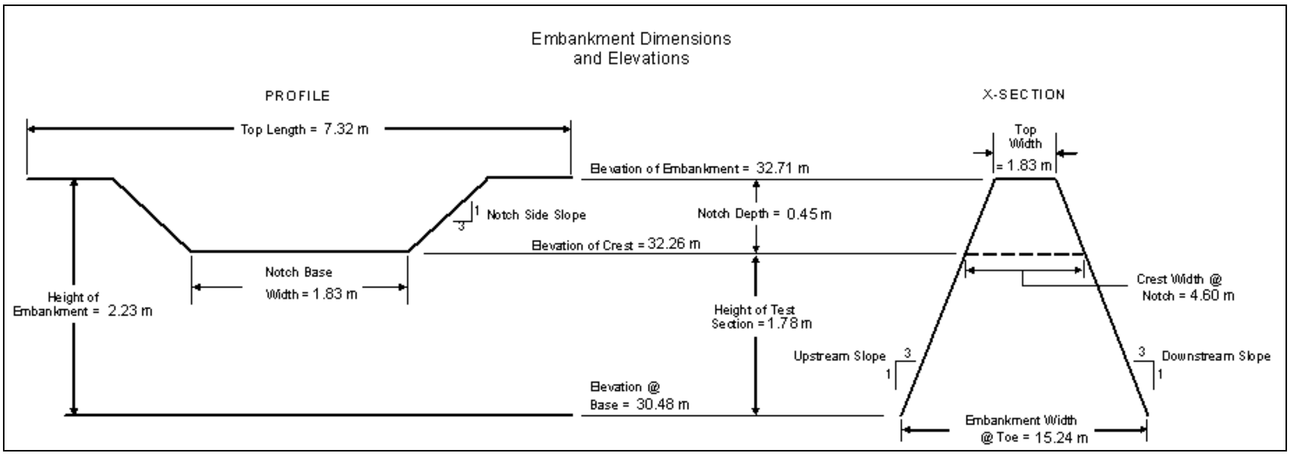


Figure 7-3: Geometry for Test Case 2

Figure 7-4: Test Case 2 embankment

Table 7-3: Embankment and test section dimensions

Embankment Dimensions		Test Section Dimensions	
Height of Embankment	2.23 m	Height of Test Section	1.78 m
Elevation of Embankment	32.71 m	Notch Base width	1.83 m
Top Length	7.32 m	Notch Side Slopes	3/1 (H/V)
Top Width	1.83 m	Notch Depth	0.45 m
Upstream Slope	3/1 (H/V)	Crest Width @ Notch	4.60 m
Downstream Slope	3/1 (H/V)	Elevation of Crest @ Test Section	32.26 m
Elevation @ Base	30.48 m		
Embankment Width @ Toe	15.24 m		

Table 7-4: Embankment soil properties

Gradation		Construction	
% Clay < 0.002 mm	26	Compaction Effort (kN.m/m^3)	191
% Silt > 0.002 mm	49	Loose Lift Thickness	0.15 m
% Sand > 0.105 mm	25	Compacted lift thickness	0.12 m
Plasticity Index	17	**Sieve Analysis**	% Finer
Soil Classification (USCS)	CL	0.002 mm	26
Grain Density (g/cm^3)	2.67	0.005 mm	32
Unconfined Compressive Strength (kN/m^2)	67.92	# 200 (0.075 mm)	75
Average Dry Density (g/cm^3)	1.65	# 10 (2.00 mm)	100
Average Water Content @ construction %	16.4		
Average Total Density (g/cm^3)	1.92		
Erodibility Coefficient kd (cm^3 /N.s)	0.04		
Critical stress τc (kN/m^2)	0.01		

7.2 Evaluation methodology

The main objective of the evaluation was to show how the performance of the three different methodologies compares over a range of conditions. This allows an understanding of how the underlying assumptions of each method (e.g. considering or not considering soil type, effect of grass type and quality, etc.) could affect the results. This, in turn, helps to conclude what method(s) could be used or updated for use in Europe.

To achieve this, a number of parameters have been chosen for the purposes of comparison. These parameters have been selected as they could significantly impact the grass performance during an overflow event. A list of the selected parameters with a brief definition is given below:

1. Maximum overflow head* which is the maximum depth of water applied on the grass during an overflow event.
2. Downstream (dry) slope which is the vertical to horizontal distance ratio.
3. Critical shear stress which is defined as threshold stress below which no soil erosion occurs.
4. Soil erodibility which represents erosion rate of the soil.
5. Soil plasticity index which is defined as the difference in moisture content between the soil liquid limit and the soil plastic limit.
6. Vegetation type which is linked to the friction of different vegetation types
7. Vegetation quality which describes the uniformity, density and length of the grass.

Since Methods 1 and 2 are velocity based whereas the third method is shear stress based (which means they use different criteria to predict the grass cover failure), it was necessary to find an approach that ensures that the performance comparison is done correctly. Therefore, the HR BREACH and the WINDAM models have been used to simulate the failure of the grass cover for Methods 1 and 2 and Method 3 respectively. Doing this avoids calculating the intermediate values whilst ensuring each test case conditions are identical - to the maximum possible extent - in both models. Details of the HR BREACH and WINDAM model versions that have been used to undertake the comparison are given in Appendix **Error! Reference source not found.**. Figure 7-5 and Figure 7-6 show the graphical user interface (GUI) of the HR BREACH and the WINDAM models respectively.

* Changing the overtopping head was achieved by lowering and raising the breach initial invert level.

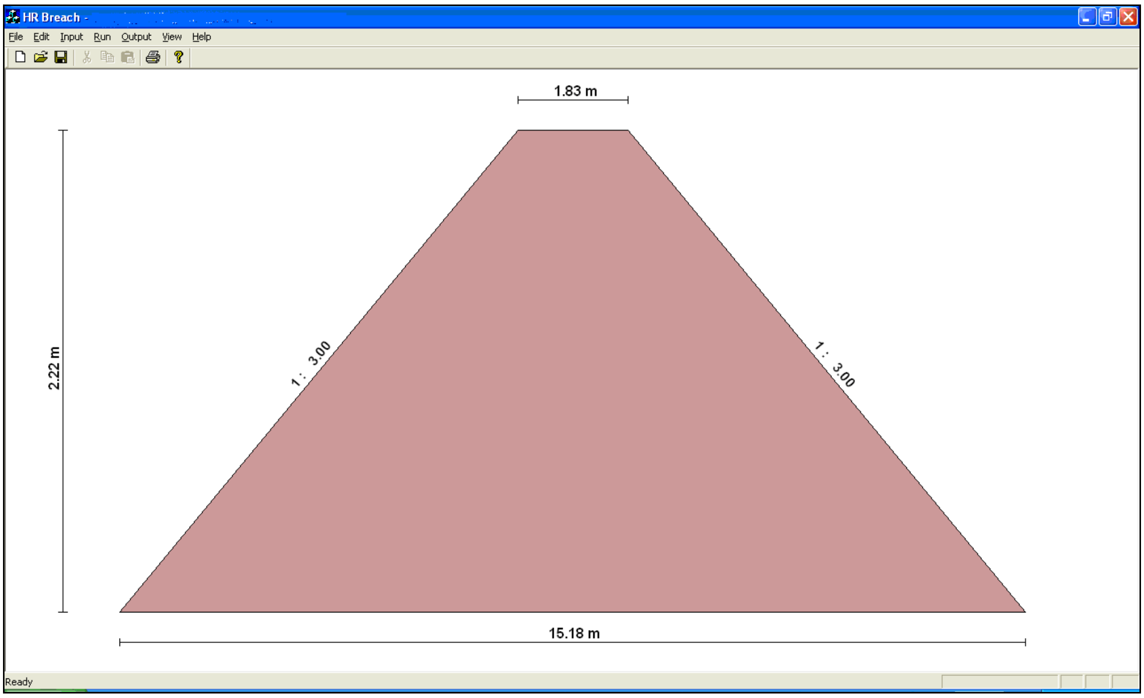


Figure 7-5: GUI of the HR Breach model

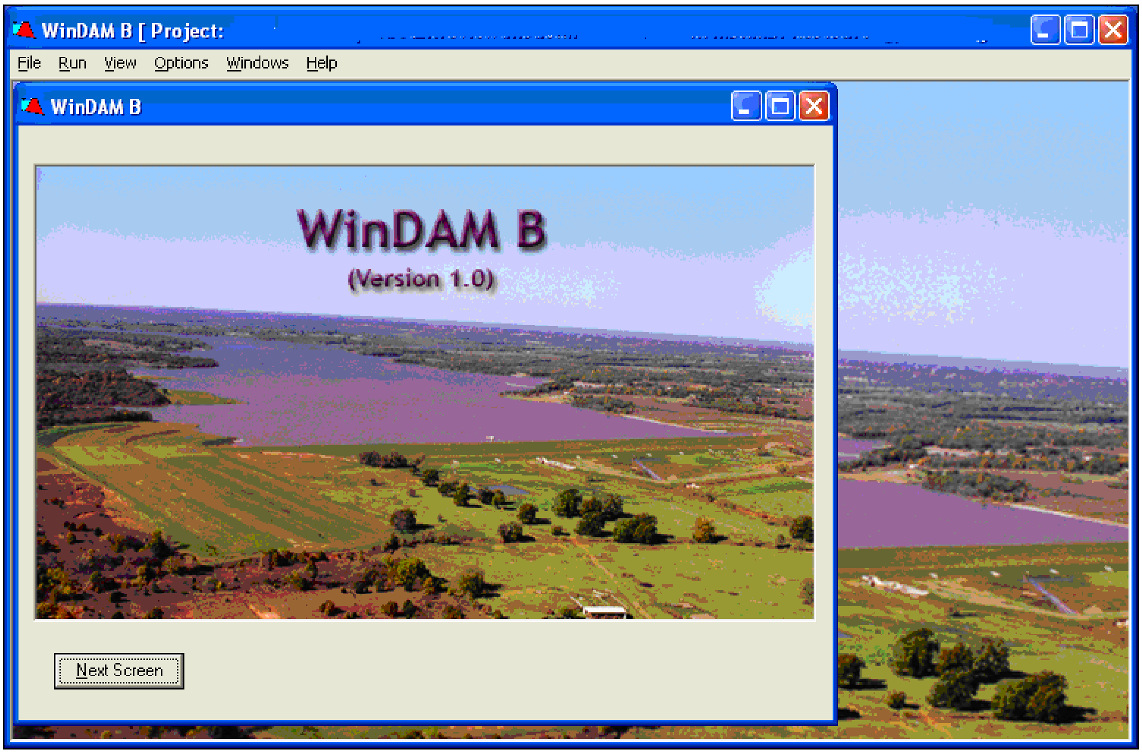


Figure 7-6: GUI of the WINDAM model

7.3 Evaluation results

In this section, the evaluation results of the test cases are presented.

7.3.1 Test case 1

Table 7-5 shows the parameter variations that were used for Test Case 1 whilst Figure 7-7 shows the results for each parameter.

Table 7-5: Parameter variation for Test case 1

Parameter	Method 1 (TN71)			Method 2 (CIRIA 116)			Method 3 (Hbk 667)		
	Base	Var. 1	Var. 2	Base	Var. 1	Var. 2	Base	Var. 1	Var. 2
Breach initial invert level (m)	32.25	31.95	32.55	32.25	31.95	32.55	32.25	31.95	32.55
Downstream (dry) slope	1:3	1:2	1:4	1:3	1:2	1:4	1:3	1:2	1:4
Critical shear stress (kN/m^2)	0.00	0.02	0.04	0.00	0.02	0.04	0.00	0.02	0.04
Soil erodibility (cm^3 /N.s)	10.2	5.1	20.4	10.2	5.1	20.4	10.2	5.1	20.4
Soil plasticity index	0	10	20	0	10	20	0	10	20
Vegetation type							Bermuda	Buffalo	Mixture / alfalfa
Vegetation quality*	Poor	Medium	Good	Poor	Medium	Good	3	2	1

The results show that for this test case some parameters do not have any impact on the grass performance in all methods. These parameters are the soil erodibility and critical shear stress. This is understandable since it was found that those parameters are not included in the grass performance assessment formulation in all of the methods. The plasticity index variations showed a significant impact for Method 3 but not for Methods 1 and 2. This can also be explained as the plasticity index is only included in formulation of Method 3. Other parameters such as the overflow head, the downstream slope and the vegetation quality shows various degrees of impact with the

* Vegetation quality is expressed as poor, medium and good in methods 1 and 2. This is equivalent to maintenance code 3,2 and 1, respectively, in method 3.

vegetation quality showing the highest impact. Vegetation type was not varied for Methods 1 and 2 as they do not inherently have this in their formulation. But, this was varied for Method 3 and surprisingly did not have any effect on the failure time of the grass. This was looked at and it could be because the grass cover had a maintenance code of 3 (i.e. poor) with short length and low density. Therefore, vegetation type features did have a significant impact on the results.

Generally, the 3 methods followed one trend for all variations which is:

1. Method 1 is the most conservative one (in the sense that it predicts the most rapid failure of the grass cover)
2. Method 3 is the most optimistic one (in the sense that it predicts the slowest failure of the grass cover)
3. Method 2 (TN71) typically lies between Method 1 and 3.

It should be also noted that for the base run, all methods predicted a slower failure than the actual failure time.

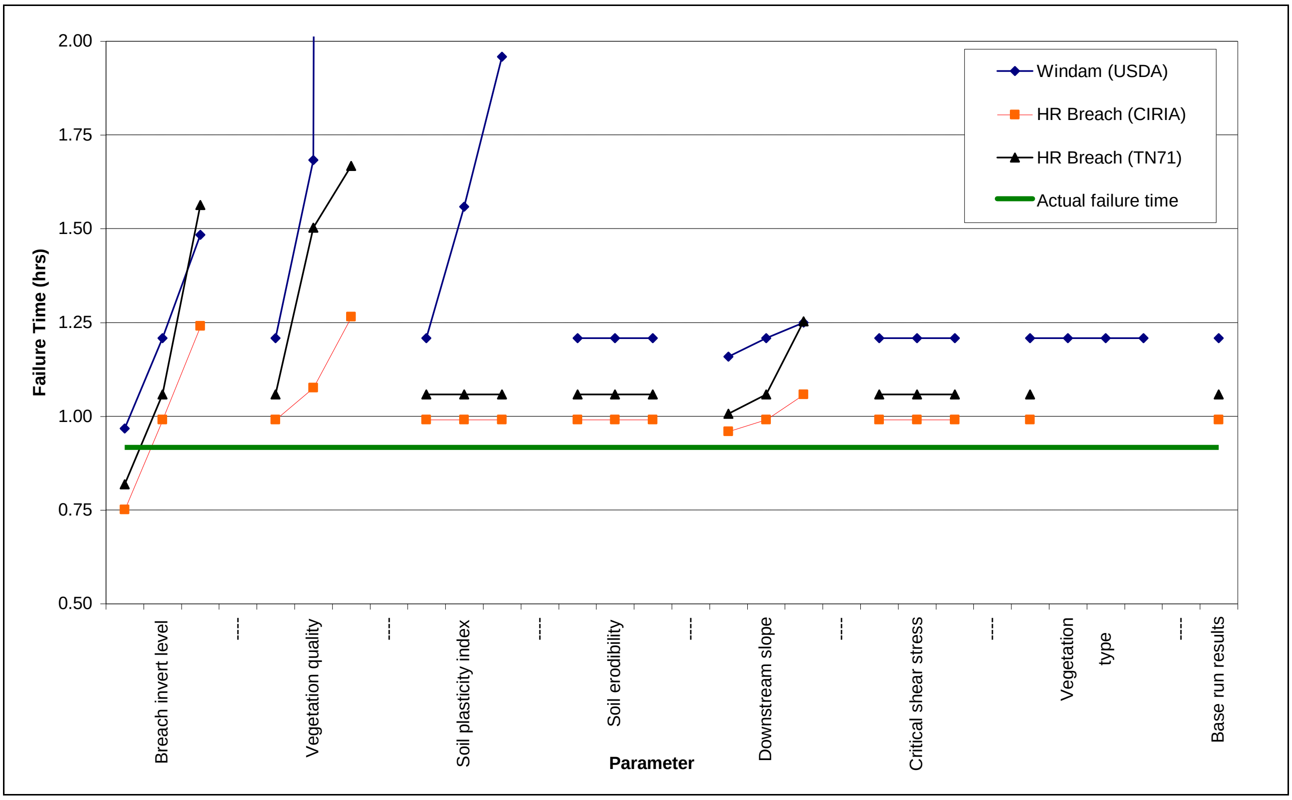


Figure 7-7: Comparison of results for Test Case 1

7.3.2 Test case 2

Table 7-6 shows the parameter variations that were used for Test Case 2 whilst Figure 7-8 shows the results for each parameter.

Table 7-6: Parameter variation for Test case 2

Parameter	Method 1 (TN71)			Method 2 (CIRIA 116)			Method 3 (Hbk 667)		
	Base	Var. 1	Var. 2		Base	Var. 1	Var. 2		Base
Breach initial invert level (m)	32.25	31.95	32.55	Breach initial invert level (m)	32.25	31.95	32.55	Breach initial invert level (m)	32.25
Downstream (dry) slope	1:3	1:2	1:4	Downstream (dry) slope	1:3	1:2	1:4	Downstream (dry) slope	1:3
Critical shear stress (kN/m^2)	0.01	0.02	0.04	Critical shear stress (kN/m^2)	0.01	0.02	0.04	Critical shear stress (kN/m^2)	0.01
Soil erodibility (cm^3 /N.s)	0.04	0.02	0.08	Soil erodibility (cm^3 /N.s)	0.04	0.02	0.08	Soil erodibility (cm^3 /N.s)	0.04
Soil plasticity index	17	0	10	Soil plasticity index	17	0	10	Soil plasticity index	17
Vegetation type	NA			NA			Bermuda	Vegetation type	NA
Vegetation quality	Poor	Medium	Good	Vegetation quality	Poor	Medium	Good	Vegetation quality	Poor

Test Case 2 results show very similar behaviour to Test Case 1. Soil erodibility and critical shear stress did not have any impact on the failure time results. The plasticity index variations showed also a significant impact for method 3 but not for methods 1 and 2 and the overtopping head, the downstream slope and the vegetation quality showed various degrees of impact with the vegetation quality showing the highest impact. Vegetation type behaviour was also identical to Test Case 1 and this also because of the low quality of the grass cover.

For this test case, the 3 methods followed the same trend of Test Case 1 which is:

1. Method 1 is the most conservative one (in the sense that it predicts the most rapid failure of the grass cover)

2. Method 3 is the most optimistic one (in the sense that it predicts the slowest failure of the grass cover)

3. Method 2 (TN71) typically lies between method 1 and 3.

The most notable difference between the results of this Test Case 2 and Test Case 1 is in the comparison of the base run failure time with the actual failure time. In this test case, methods 1 and 2 predicted faster failure while method 3 was still slower.

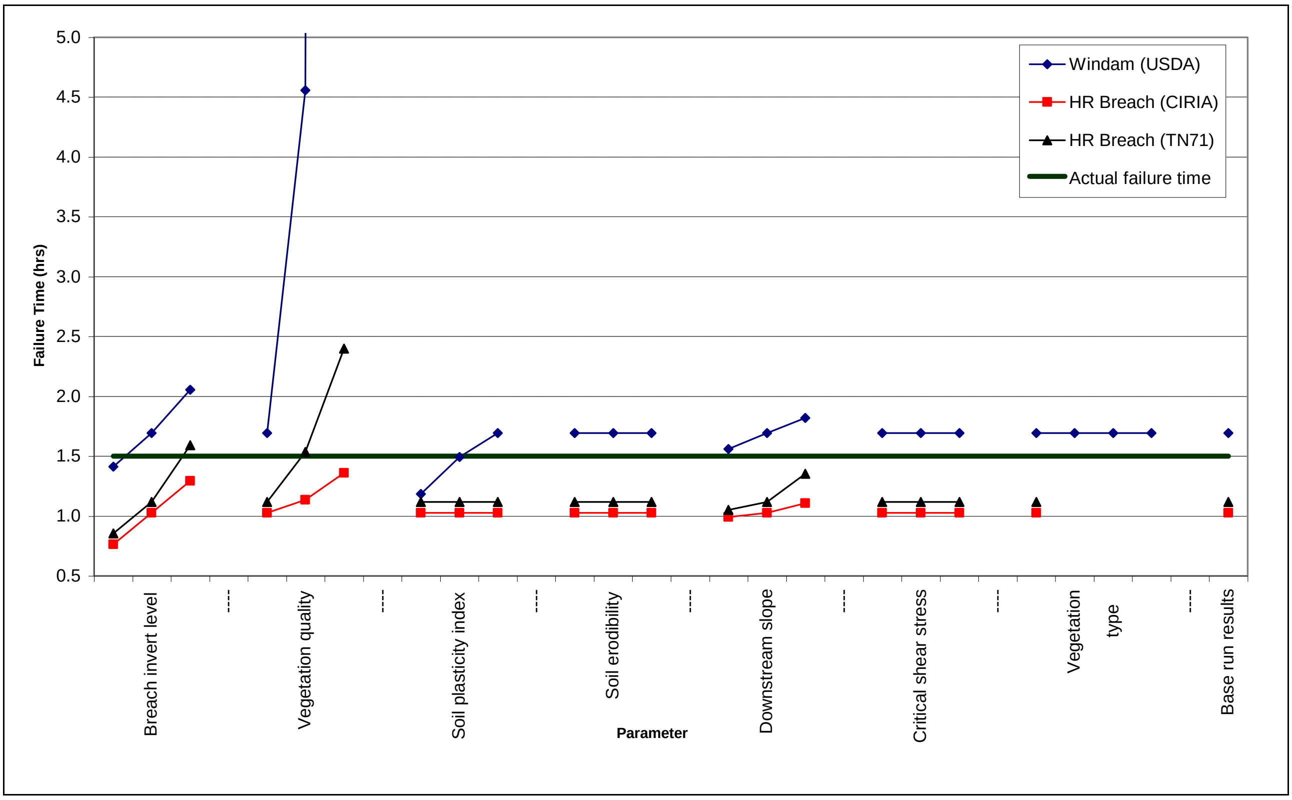


Figure 7-8: Comparison of results for Test Case 2

8 Conclusions and recommendations

The review of current guidance, and the data upon which this guidance is based, highlighted some noteworthy issues:

1. Practical and detailed quantitative guidance on performance of grass under overflow conditions is quite hard to find. There appear to be many research initiatives, but little generic guidance with actual methods provided for the design or performance analysis of grass cover. To the contrary there seems to be plenty of general guidance on the maintenance and use of vegetation.

2. A lot of research initiatives seem to focus on the hydraulic resistance of grass / vegetation to flow, rather than performance of the grass in protecting soil from erosion.

3. Based upon the literature review undertaken, the main sources of guidance on erosion protection from grass cover seem to be limited to:

   a. A guide to the use of grass in hydraulic engineering practice (Whitehead, 1976) – CIRIA Technical Note 71.
   b. Design of reinforced grass waterways (Hewlett et al, 1987. CIRIA Report 116).
   c. Stability Design of Grass-Lined Open Channels – Agriculture Handbook 667 (Temple at al, 1987).

   It should be noted that the CIRIA 116 method builds from the CIRIA Technical Note 71 data. It also incorporates USDA data, hence all three methods are related to some degree.

4. The extent to which US grass performance data is valid in Europe remains unclear. Where grass performance is related to root density, soil strength etc. it would seem ‘transferable’, but research looking at this issue does not appear to have been undertaken. The CIRIA 116 design guidance does incorporate US data within the analysis.

The method comparison highlighted some interesting issues:

1. The CIRIA 116 design curves consistently predicted quicker grass failure times than the CIRIA Technical Note 71 data. This is consistent with the inclusion of a factor of safety into the CIRIA 116 performance curves (Morris et al, 2010). Users of the CIRIA 116 curves should note that a factor of safety has been included since the relevance of this differs if the curves are used for design or performance / reliability assessment (with design leading to a safer design, whilst with performance assessment, leading to a pessimistic assessment of behaviour).

2. The USDA approach incorporates the plasticity index, which reflects to a degree, the soil erodibility (Morris, In Prep). This shows a significant variation in performance, as soil erodibility reduces, whereas the CIRIA methods show no variation, because soil parameters are not considered.

   It would seem logical that the physical process of grass erosion, with the removal of roots from the soil, would also relate to the resistance of the underlying soil to erosion. The trend in breach analysis is towards the use of soil erodibility in order to improve representation of the embankment performance. Similarly, with the likely trend being towards design or planning for acceptable over flow during increasingly extreme flood events, adoption of a method that includes representation of soil erodibility would seem sensible.

8.1 Remaining gaps in knowledge

The research undertaken has confirmed that existing guidance is based upon quite limited data sets, some of which originates from the USA and most of which relates to grass lined channels rather than overflow on flood embankments.

Three prediction methods were identified during the study, two of which are directly related, being methods from sequential studies. The third is also linked, having provided some of the data used within the other two studies. This reinforces concerns that all of the guidance found within this review originates ultimately from the same sources, albeit with some added data or data variations between the different publications.

One original aim of this work was to review and possibly analyse data from the earlier research in order to see whether more could be learned without the need for fresh field testing. Unfortunately, since all of the base data originates from the 1980's or earlier, it was found that access to the data was not possible; original reports, paperwork etc. detailing the research are no longer available. Consequently, the analysis reported here focussed on comparing the different methods to see whether they were significantly different and whether there were any obvious limitations.

The two main conclusions were that:

i. The CIRIA 116 report contained design curves, most likely with an embedded factor of safety (in comparison to the earlier TN71 report and curves). As such, using the earlier TN71 data gives a more precise prediction of performance, which is more appropriate for use in the performance analysis of flood embankments.

ii. The USDA approach includes a measure of the underlying soil performance, via inclusion of the soil plasticity index. This allows for greater variation in grass performance, as compared to the UK CIRIA methods, since the soil parameter adds another variable that can be 'controlled'.

Hence, whilst improvement in the reliability of performance assessment can be made by using the USDA instead of CIRIA methods, there still remain a number of 'gaps in knowledge' relating to grass performance. These include:

1. The appropriateness of using test data from grasses in the USA for application within Europe.
2. The performance of grass during the initial hour or so of overflow – this period is missing from the CIRIA 116 / TN71 work.
3. Much of the data used relates to flow in steep grass lined channels, as might be used for embankment dam spillways. The applicability to small earth flood embankments is not completely clear.
4. The effect of variation in grass type in Europe is unclear. In addition, as climate change effects start to change the rainfall and soil moisture content, variations in grass type may also occur.
5. Analysis of any link between grass type and performance in conjunction with underlying soil type and performance is also required. For example, where the underlying soils are highly erosion resistant, do they prevent growth and maintenance of an effective grass layer?

Conversely weak erodible soils promote stronger grass growth? Which combination of soil and grass cover offers the best solution for flood embankment protection and performance?

6. It was noted that in recent years there have been a number of initiatives looking at (i) the management of grass (i.e. cutting frequency), (ii) soil erodibility and (iii) wave overtopping on grassed embankments. The missing piece to this jigsaw of research is quality data relating to the performance of a range of grass types, on a range of soil types under steady overflowing conditions. Such data would permit most of the gaps in knowledge listed above to be answered and for more reliable performance guidance to be given.

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10 Appendix 1: Source of information for literature review

The literature review, presented in this report, focused on the work that was, currently being or will be undertaken in Europe, the USA and other countries worldwide where vegetation performance has been studied such as China.

The sources of the literature review presented in this report were:

- Internet web based search.
- Previous knowledge gained or literature undertaken by the authors.
- Personal communications with key organisations and researchers who are active in the vegetation performance field.

In the following sections, more details are given for each source.

10.1 Internet web based search

General web base search was carried out using the Google search web site (www.google.co.uk) the following list of keywords have been used either individually or collectively in the search (sorted alphabetically):

- Bioengineering
- CIRIA and EA (UK)
- ComCoast
- Embankment
- EroGrass
- Failure
- Flooding and floods
- Grass and reinforced grass
- Guidelines and guidance
- Handbook
- IJkdijk – LiveDijk
- Levee
- Overtopping simulator

- Performance
- Protection
- SBW project
- URBEM
- USACE
- USACE
- USDA
- Vegetation

The search has resulted in identifying a considerably long list of publications, reports, technical notes, guides and handbooks. This list was filtered to identify those items that are related to grass performance.

10.2 Previous knowledge gained or literature undertaken by the authors

Two of the authors of this report (Mark Morris and Mohamed Hassan) have undertaken a literature review as part of their PhD theses. These included literature on grass performance. The literature identified within their theses formed an initial point to collect further literature. References to their PhD theses are given below:

1 Mohamed, M. (2002). Embankment Breach Formation and Modelling Methods. PhD. Thesis, the Open University, UK.

2 Morris, M. W. (In Prep). Breaching of earth embankments and dams. PhD. Thesis, The Open University, UK. (Subject to examination).

The third author (Manuela Escarameia) has extensive experience in river protection works including grass, published the “River and Channel Revetments; a design manual” book in 1998 and is an author or co-author of over 50 reports and technical papers on hydraulic structures and river engineering. She has developed the concept and tested application of grassed channels for drainage of motorways in the UK. References to her related work that contributed to this report are given below.

Escarameia M. River and channel revetments. A design manual. Thomas Telford, ISBN 0 7277 2691 9, 1998.

Escarameia M, Gasowski Y and May R. Grassed drainage channels – hydraulic resistance characteristics. Proc. ICE, Water & Maritime Engineering, Vol 154 Issue 4, December 2002.

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10.3 Personal communications with key organisations and researchers who are active in the vegetation performance field.

Direct communication with researchers involved in the earlier CIRIA and USDA work was undertaken and their feedback incorporated. Henry Hewlett provided comments on the earlier CIRIA work, whilst Greg Hanson and Darrel Temple (from USDA, ARS-HERU, Stillwater Oklahoma) commented on the USDA Handbook 667 work. All comments and contributions were gratefully received.

11 Appendix 2: Details of the HR BREACH and WinDAM B Models

11.1 The HR Breach model

The model version that was used within this research was V4.1 developed at HR Wallingford Ltd. The model was used to evaluate the capabilities of Methods 1 and 2 in predicting grass failure (See Section 7). To keep the document concise details of the vegetation module in HR Breach are given below. For full details of the model see publications by Mohamed (Mohamed 2002) and Morris (Morris, In prep).

The following assumptions are made to model the failure of the protection layers in the HR Breach model:

1. The protection layer on the downstream face of the embankment has a major effect on the breaching process and should be considered.
2. The effect of the protection layer on the crest and the upstream of the embankment on the breaching process is minor and can be neglected.

Two types of protection layers are described below. They are plain grass and reinforced grass.

The earth surface of an unlined waterway is liable to erosion by high velocity flow. Where flow is intermittent, a grass cover might be used to provide protection against erosion. Plain grass has long been acknowledged as a low-cost means of protecting and stabilising an earth surface that is subject to an intermittent flow (Hewlett et al, 1987). By reinforcing the grass cover, the resulting armour layer will enhance the erosion resistance and reduce the risk of failure of grass protection (Hewlett et al, 1987). The principal application of reinforced grass is in steep waterways such as auxiliary spillways and protection of embankments against erosion by overtopping during extreme events.

Two methods of quantifying the resistance of the grass cover have been identified in the literature: They are:

1. The allowable shear stress concept (Temple, 1987).
2. The limiting velocity concept (Hewlett at al, 1987).

The second method was selected to model the failure of the grass protection as it was developed for plain and reinforced grass while the first is developed for plain grass only. Secondly, the second method has proved satisfactory for the design purposes in the UK (Hewlett at al, 1987). While the other, to the author’s knowledge, has not been tested in the UK. Thirdly, the second method is simpler to implement and use.

The procedure described below to model the failure of plain and reinforced grass was adapted from the Construction Industry Research Information Association (CIRIA) report No. 116 (1985) “ Design of reinforced grass waterways ”. The concept is based on the following:

- The water flows over the grass cover with a certain velocity.
- The grass can resist the erosion up to an upper limit flow velocity (Limiting Velocity).
- The condition of the grass cover might deteriorate with time so its limiting velocity value might decrease with time.
- After reaching the limiting velocity of the grass cover, it will start to fail and the earth surface below the cover will be liable to erosion by the overtopping flow.

The procedure described above has been numerically modelled as follows:

1. The overtopping flow is calculated as using the broad crested weir equation.
2. The flow velocity on the downstream face of the embankment is calculated using the computed flow and Manning's equation, assuming that normal flow conditions will be established along most of the steep slope of the downstream face, as follows:

$$U = R^{2/3} S_b^{1/2} / n$$

where: U : Mean velocity of the flow.

R : Hydraulic radius ≈ d (d : Flow depth).

S_b : Slope of the downstream face.

n : Manning's roughness coefficient (Also called retardance coefficient in the CIRIA report No. 116).

The retardance coefficient of the grassed surface depends on the physical characteristics of the grass sward such as its height, stiffness, and density and/or its interaction with the flow. The interaction with flow can be divided into the following three categories based on the hydraulic loading (See Figure 10-2):

- The flow depth is significantly less than the height of the vegetation that is not deflected, and the velocity at the soil surface is low due to the interference effect of the vegetation.
- The combined effect of increasing the flow velocity and the depth causes the vegetation to deflect and oscillate in the flow.
- The velocity is high enough to lay down the vegetation and a relatively smooth and stationary surface is presented to the flow. The effective height of the vegetation is then considerably less than its natural height.

The last regime is generally encountered in steep waterways. Hewlett et al (1987) reported that on these steep slopes the grass tends to be laid down by the flow and the retardance coefficient appears to be independent of the hydraulic loading and the grass length but varies with the slope of the waterway.

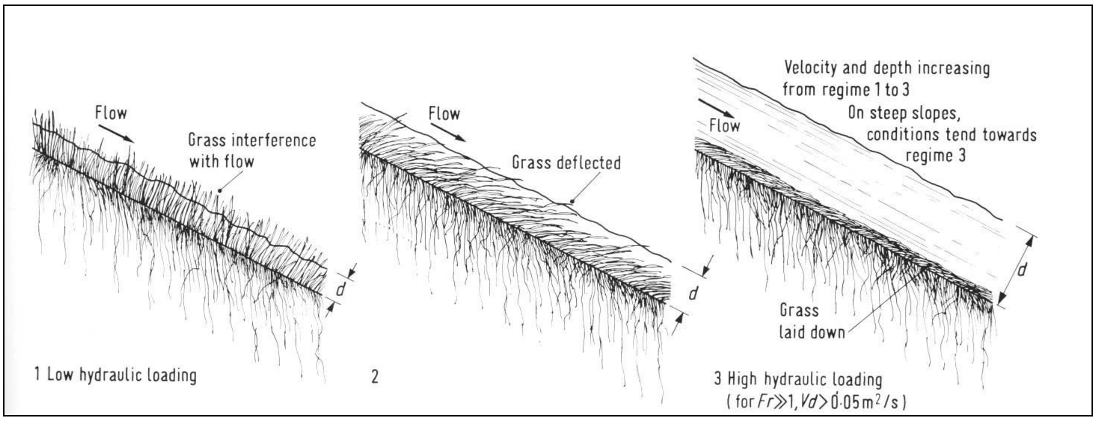

Figure 11-1: Effect of hydraulic loading on grassed surface (Hewlett et al, 1987)

Figure 4-4 in the guidance shows recommended values of the retardance coefficient for steep grassed slopes. Hewlett et al (1987) also mentioned that there is insufficient justification to warrant adopting different values of hydraulic roughness for any reinforced grass systems from those used for plain grass, where grass is sufficiently long to cover the surface.

3. The calculated velocity is compared to the limiting velocity represented in Figure 4-1 for Method 1 or Figure4-3 for Method 2.

4. The procedure is repeated talking into account the total time elapsed until the calculated velocity exceeds the limiting velocity.

The limiting velocities for a duration of less than one hour was assumed to be the same as for a duration of one hour. This assumption has been confirmed by one of the authors of the CIRIA report, H. Hewlett, in a personal communication by email.

11.2 The WINDAM model

The version that was used within this work package is WINDAM B version 1.0 developed by USDA and USACE in cooperation with Kansas State University . It was used to evaluate the capabilities of Method 3 in predicting grass failure (See Section **Error! Reference source not found.**). To keep the document concise details of the vegetation module in WINDAM B are given below. For full details of the model See (ftp://ftp.wcc.nrcs.usda.gov/wntsc/H&H/WinDAM/FTPdownloadHelp.html).

For vegetation (grass), the basis for evaluation of the hydraulic attack is that applied to (surface) failure of vegetated earth spillways (NRCS, 1997). The computed attack is based on the assumptions of stepwise steady flow conditions and normal depth on the slope as computed by Manning's equation in the form (English units):

$$d_n = \left(\frac{qn}{1.49\, S^{1/2}} \right)^{3/5}$$

Where: d_n= the normal depth on the slope in feet,

n = Manning's roughness coefficient,

S = the embankment slope expressed as the sine of the angle with the horizontal, and

q = the unit discharge on the slope in cfs/ft.

Two forms of hydraulic attack are evaluated. These are the gross stress and the time integral of the erosion effective stress. For this purpose, the gross stress is computed as:

$$\tau_o = \gamma d_n S$$

Where τ_o= the gross stress,

γ= the unit weight of the water, and the other variables are as previously defined.

The erosion effective stress on the soil supporting the vegetation is computed from the relation:

$$\tau_e = \tau_o (1 - C_F) \left(\frac{n_s}{n} \right)^2$$

Where: τ_e= the erosion effective stress,

C_F=the vegetal cover factor,

n_s=the soil grain roughness expressed as a Manning's coefficient, and the other variables are as previously defined.

Guidelines for determining the vegetal cover factor for uniform grass covers are given by Temple et al. (1987). For covers with discontinuities such that erosion takes place within the discontinuity, CF is set to zero (NRCS, 1997). For covers having major discontinuities such that the flow is concentrated in the discontinuity, the above equation is applied with the local effective value of Manning's coefficient equal to the soil grain roughness thereby making the erosion effective stress equal to the gross stress (NRCS, 1997).

The soil grain roughness for use in the above equation is computed from representative particle diameter using the relation presented by Lane (1955) expressed in the form:

$$n_s = \begin{cases} 0.0156 & D_r \leq 0.05 \\ \dfrac{D_r^{1/6}}{39} & D_r > 0.05 \end{cases}$$

Where Dr is the representative soil diameter in inches. In application, the representative soil diameter for use in the above equation is normally taken to be the particle diameter for which 75% by weight of the material is finer.

The value of Manning's coefficient for the vegetated slope is computed from the relation (Temple et al., 1987):

$$n = e^{C_I \left[0.0133\ln^2(q) - 0.0954\ln(q) + 0.297\right] - 4.16} \qquad 0.0025C_I^{2.5} \leq q \leq 36$$

With the variables as previously defined and q expressed in cfs/ft. When q is outside of the indicated bounds for the above equation, the value of n is set to that computed for the nearest bound.

In application, the uniformity of the vegetal cover is specified by a maintenance code having a value of 1 (uniform cover), 2 (minor discontinuities), or 3 (major discontinuities). Determination of the appropriate code is somewhat subjective and additional research and analysis is needed to better quantify the effects of various sizes and types of discontinuities. For present application, minor discontinuities are those which locally expose the soil to erosive attack over an area on the order of the stem length and/or flow depth without causing flow concentrations. Major discontinuities are those which cause the unit discharge to locally increase as well as locally exposing the soil to erosive attack. The ideal condition of uniform cover over the entire embankment face providing optimal protection from erosion would be unusual under field conditions.

Integration of the erosion effective stress over time to determine the point of effective failure of the vegetative cover implies a failure mode of soil erosion through the vegetative cover. The value of the integral corresponding to cover failure is given by (NRCS, 1997):

$$\int_{o}^{t_f} \tau_e \, dt = 0.2 I_w + 1$$

Where: t_f= the time corresponding to failure with time expressed in hours,

τ_e= the erosion effective stress expressed in lb/ft2, and

I_w= the plasticity index of the soil material being eroded.

The above equation was developed empirically using data from vegetated earth spillways and a relatively fine grained soil material capable of supporting vegetation is implied. As implemented in WinDAM, the integration is carried out by treating the conditions computed for the beginning of the time step as constant through the time step. For the erosion driven failure mode implied by the above equation to be applicable, the vegetal cover must be adequately rooted in the soil and the total stress must be less than that required to directly remove the vegetal elements. Therefore, a limit is also placed on the gross stress computed by the Manning's equation. For application in the WINDAM model, this limit is set 13.5 lb/ft2 corresponding to a rooting depth of approximately 1.5 ft in the relations developed for spillway application (NRCS, 1997). As implemented, the vegetal protection evaluation portion of the model is not considered applicable to conditions where the potential rooting depth is less than 1.5 ft.