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Application of Dutch reliability-based flood defence design in the UK

F.A. Buijs, P.H.A.J.M. van Gelder, J.K. Vrijling & A.C.W.M. Vrouwenvelder
Delft University of Technology, Delft, Netherlands

J.W. Hall
University of Bristol, Bristol, UK

P.B. Sayers
HR Wallingford, Wallingford, UK

M.J. Wehrung
Road and Hydraulic Engineering Division of the Dutch Ministry of Transport, Public Works and Water Management, Delft, Netherlands

ABSTRACT: Increasing concern about recent and potential impacts of flooding in the UK are leading to the adoption of risk-based methods for planning, appraisal, design and operation of flood defences. Probabilistic methods for assessment and design of flood defences are relatively well developed in the Netherlands because of the potentially devastating impacts of flooding. However, for reasons described in this paper, reliability methods developed in the Netherlands are not universally applicable in the UK context. This paper describes a test application of a reliability method developed for ring dykes in the Netherlands to the flood defence system at the Caldicot Levels in South Wales. Although constrained by data limitations (even at this relatively data-rich site, by UK standards) the reliability method provides estimates of the probability of failure of the flood defence system, identifies weak system components and identifies which parameters contribute most to the probability of failure. The study has provided recommendations for the future development of reliability-based methods for flood management in the UK.

1 INTRODUCTION

In The Netherlands as well as in the UK flood protection policy is currently undergoing changes towards a risk-based approach of flood defences. A risk-based safety approach takes into account the strength and the loading conditions of the flood defence system as part of the probability of inundation as well as the consequences of inundation in case of failure of the flood defence system. TAW (2000) points out that a risk-based analysis of flood defence systems can result in the identification of the system's weak areas and can therefore enable the decision-maker to target improvement schemes and maintenance activities. Another advantage is that in case of large scale flood defence improvements the decision-maker can compare different design options in terms of the actual risk reduction and the costs which are associated with the improvement options. In the light of the shift to a risk-based safety approach the UK Environment Agency and the Department of the Environment, Food and Rural Affairs, which together have responsibility for flood defence policy and implementation in the UK have launched a research and development project called RASP: Risk Assessment of flood and coastal defences for Strategic Planning. This project aims to develop tiered methodologies for risk assessment of flood defence systems: a high level methodology supporting national policy making, an intermediate level methodology supporting regional policy making and a detailed level approach supporting policy making at the scale of one flood defence system.

2 OBJECTIVE AND DETAILED WORKING METHOD

The objective of this research is to apply a reliability analysis to the Caldicot Levels' flood defence system in the UK using Dutch reliability methods for flood defences in order to support an evaluation of the appropriateness of these methods as part of the detailed level methodology in RASP. The main working-method is derived from CUR report 190 (1997) and involves carrying out the reliability analysis by taking the following steps (see Figure 1 details).

Definition of the Caldicot Levels' flood defence system and its components.

– Analysis of the failure modes connected to the components
– Modelling the Caldicot Levels' flood defencec system and expressing this model into data

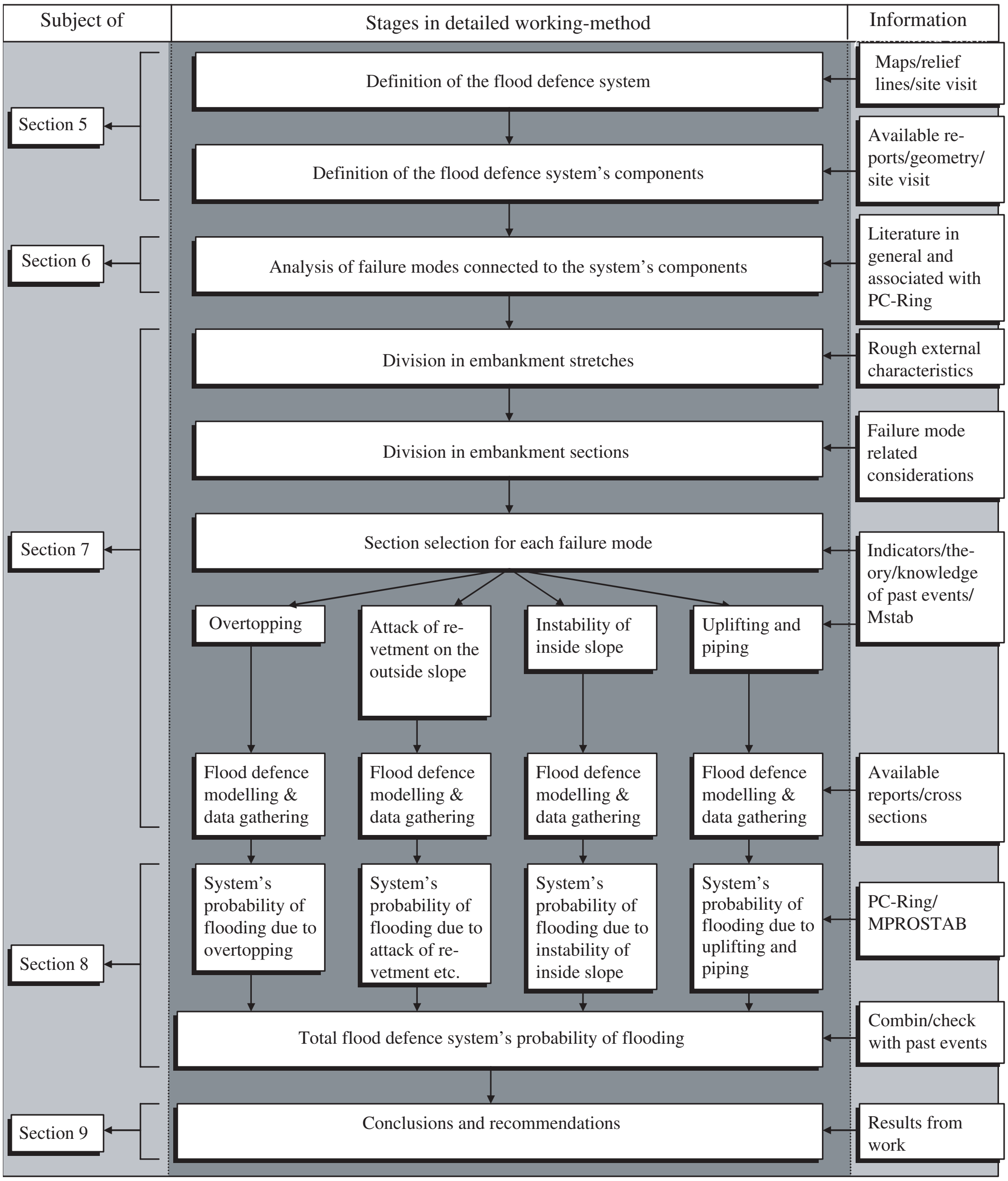

Figure 1. Detailed working-method.

– Calculation of the probability of flooding of the Caldicot Levels' flood defence system.

Two scenario's are subject of the reliability analysis:

1. The present Caldicot Levels' flood defence system
2. The same system after a number of planned improvements have been taken into account

Before these steps are discussed in more detail the boundary conditions and the Dutch reliability methods for flood defences which form the framework of the reliability analysis are addressed.

3 DESIGN LEVELS

The Caldicot Levels' flood defence system is located at the south coast of Wales in the UK. The system borders the Severn Estuary in the south, the river Usk in the west and a distinct line of hills in the north and east, see Figure 2. ABP Research (2000) provides information on the local water level, wind speed and wave conditions. In the Severn estuary one of the largest tidal ranges in the world occurs, varying between 9 m and 15 m. The largest fetches and the most severe wind speeds are related to the south westerly wind directions. The River Usk is a small river, however the water levels can reach relatively high values especially in case of high water levels at the Severn Estuary. The mean elevation of the Caldicot Levels is OD + 5.5 m which compares to mean tide high water levels of OD + 4.8 m, mean spring tide high water levels of OD + 6.5 m and a 200-year return period water level of OD + 8.55 m. The crest levels of the flood defence system vary between OD + 8 and OD + 10 m. According to WS Atkins (1999), the embankments and soil underneath consist mainly of clay. Finally, in WS Atkins (2000) information is available of areas which have been subjected to damage caused by a number of storms in the past and which can be considered as weak.

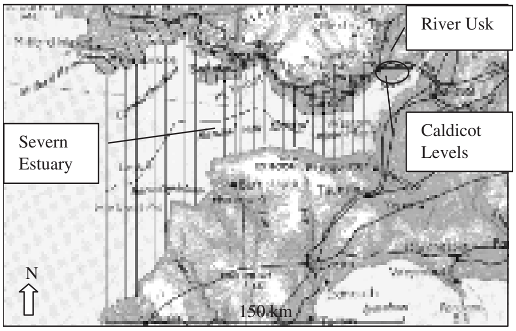

Figure 2. Location of the Caldicot Levels' flood defence system with respect to the Severn Estuary and the Usk.

4 DUTCH RELIABILITY METHODS FOR FLOOD DEFENCES

4.1 *Calculation of annual probability of failure*

4.1.1 *Failure modes*

The following failure modes are included in the calculation of the annual probability of flooding of the flood defence system:

– Overtopping or overflow discharges pass the embankment crest and consequently failure occurs either due to damage and erosion of the inside slope or due to saturation of the clay cover layer soil leading to instability of the inside slope.
– Instability of the inside slope of the embankment. The extreme outside water levels result in different water pressure distributions in the embankment body. The geotechnical equilibrium (according to Bishop) of the ground body is affected in such a way that instability of the inside slope occurs.
– Uplifting and piping. The hydraulic uplifting force exerted by the water head difference between the outside and inside water levels leads first to bursting of the impervious foundation layer of the embankment. After uplifting of the impervious layer, water flow as a result of the hydraulic head difference causes the development of pipe shaped erosion in the burst impervious layer.
– Damage of the revetment on the outside slope and consequently erosion of the embankment body. Attack of the revetment on the outside slope by the water and wave conditions causes damage to the revetment. The embankment body is exposed to the same hydraulic conditions after the revetment has been damaged. Erosion of the embankment body can lead to breach.

A more detailed description of the failure modes and the reliability functions which represent these failure modes is given in Vrouwenvelder et al. (2001) and Lassing & Vrouwenvelder (2003).

4.1.2 *Statistics*

The statistical character of the random variables in the reliability functions consists of statistical distribution functions and correlations in time and space. The correlation in time is modelled according to Borges Castanheta. This model assumes constant correlations during and between time intervals. The spatial correlation of random variables in a section is assumed to decrease to a constant value after a certain length along the flood defences. The statistical models of the water levels and wind speeds involves a set of basic random variables of water levels and wind speeds at the mouth of the Severn Estuary (Figure 2). These basic variables are transferred to local water levels and wave conditions by use of a numerical model like for instance

Mike11, Sobek, SWAN, HISWA, DELFT 3D, etc. The statistical distribution functions and the correlations between water level and wind speed are applied to the basic random variables at the mouth of the estuary. Detailed information can be found in Vrouwenvelder et al. 2001.

4.1.3 *Calculation methods*

Calculations at the level of one reliability function are made with: FORM, SORM, crude Monte Carlo, Directional Sampling. Detailed information about these methods can be found in Vrouwenvelder (2001) and Vrijling & Van Gelder (2002).

In Vrijling & Van Gelder (2002) a method is presented to calculate an annual probability of failure of a flood defence system involving a number of different reliability functions representing: one failure mode, cross section, tide, wind direction. These different reliability functions are combined to one remaining equivalent reliability function. During this process mutual correlations between the functions are taken into account.

In order to perform these calculations software called PC-Ring has been applied, see Figure 1. Besides the failure modes of dikes, PC-Ring contains the possibility to calculate the probability of failure of dunes and structures. The latter is calculated in connection to failure due to piping and failure to close of the structure in case of a storm.

4.1.4 *Description of calculation results*

The calculation of the annual probability of flooding of the Caldicot Levels' flood defence system results among others in:

- Annual probabilities of failure and reliability indices of β the sections which are included in the calculations.
- Coefficients of influence, α-values, that point out which random variables contribute most to the total uncertainty of the reliability function.
- The total annual system's probability of flooding due to one failure mode and the weakest link in the system.
- The total annual system's probability of flooding.

4.2 *Selection of weak flood defence sections*

The amount of work related to data gathering is reduced by a process which aims to select the sections that are most representative of the system's probability of failure. This process starts with dividing the flood defence system into stretches, and more detailed sections. The cross sectional and statistical properties are assumed to be constant along one section. By use of indicators, which are based on rough information, sections are selected which are considered as weak. These selected cross sections dominate the total probability of failure and are therefore included in the calculations with PC-Ring. This process is described in Calle et al. (2001).

5 DEFINITION OF THE FLOOD DEFENCE SYSTEM AND ITS COMPONENTS

The Caldicot Levels' flood defence system is defined as shown in Figure 3. The line south of the locations marked A and B represents the relevant defence length for the calculation of the probability of inundation. The OD + 10 m relief line defines the boundary formed by the high grounds. The area between the lines suffers consequences in the form of partial or complete flooding if the flood defence system fails at one or more locations. The components are also indicated in Figure 3.

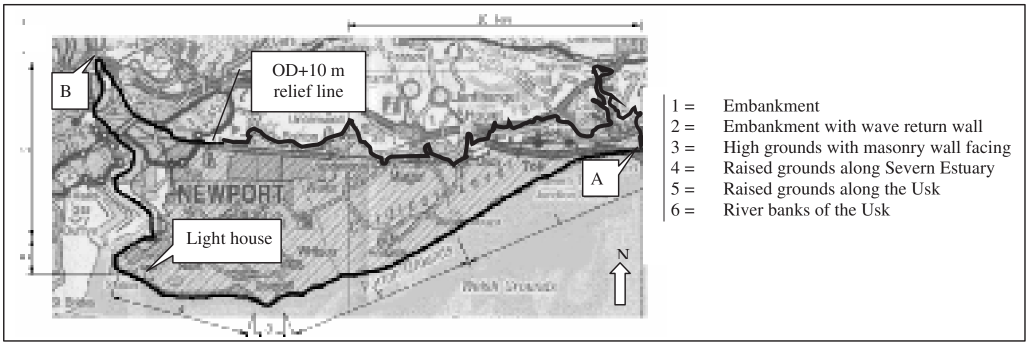

Figure 3. Definition of the Caldicot Levels' flood defence system's boundaries. The OD + 10 m line represents the high grounds which do not contribute to the system's probability of flooding. Additionally, the figure includes a rough indication of the position of the main flood defence components (from Chatterton (2001)).

6 ANALYSIS OF THE FAILURE MODES CONNECTED TO THE COMPONENTS

6.1 *Failure modes of present flood defence system*

All of the components except for the embankment with wave return wall, are calculated with the failure modes which are present in PC-Ring (see subsection 4.1.1). Below the main flood defence components which are also mentioned in Figure 3 are listed with the failure modes which have been considered in the calculation:

- Embankment: Overtopping, instability inside slope, piping, attack of the revetment on the outside slope (grass).
- Embankment with wave return wall: Overtopping, instability inside slope, piping, attack of the revetment on the outside slope (rock armour). In case of the present flood defence system the effect of the wave return wall on the overtopping is assumed to be negligible. The approach of the wave return wall in case of the improved system is described in subsection 6.2.
- High grounds with masonry wall facing: Only overtopping is taken into account and approached with a limit critical discharge value instead of the grass/erosion or saturation models. The high grounds are regarded as broad embankments with shallow slopes. Therefore, the contributions to the total probability of flooding by the failure modes instability inside slope, piping, attack of the revetment on the outside slope are assumed to be small.
- Raised grounds along the Severn Estuary are approached in a similar way as high grounds with masonry wall facing.
- Raised grounds along the River Usk: see raised grounds along the Severn Estuary.
- The river banks of the Usk: failure is represented by the return period of the river water level exceeding the highest elevation of the river bank.

6.2 *Failure modes of improved flood defence system*

The main flood defence components will be improved in future. These improvements concern mainly raising of the flood defences along a considerable length and the replacement of the present wave return wall by a higher and more effective one. For all the flood defence components except the embankment with wave return wall the selection of failure modes remains the same for the present and the improved system. For the improved form of the embankment with wave return wall an approach is developed which takes the wave return wall into account.

Theoretically speaking, the wave return wall reduces the amount of overtopping and failure of the wave return wall does not necessarily need to lead to failure of the complete embankment (upper part of Figure 4). However, this approach leads to practical complications of the implementation of the wave return wall in PC-Ring. Therefore, the practical approach as illustrated in the lower part of Figure 4 was applied. This approach is based on the assumption that when the wave return wall fails the entire embankment also fails.

Analysis of the results of the calculations will point out whether the probability of failure of the wave return wall is high or low relative to that of the embankment. If this is high, the probability of failure of the embankment dominates the probability of failure. If it is low, the practical approach applies, the probability of failure is dominated by the highest of the following two values: probability of failure of the wave return wall or the probability of failure of the embankment with wave return wall as a whole.

Two failure modes of the wave return wall are taken into account: horizontal sliding or tilting (see Table 1). The force is formed by the wave impact and the strength is mainly determined by the weight of the wave return wall. The model which is applied to determine the wave impact pressures is described in Martin (1999).

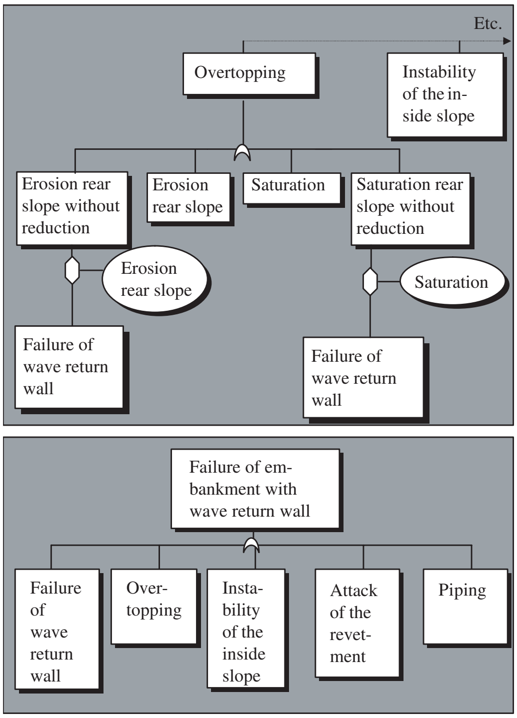

Figure 4. Fault tree of theoretical approach of wave return wall (top) and of practical approach as implemented in PC-Ring (bottom).

Table 1. Failure modes of the wave return wall which have been incorporated in PC-Ring.

Reliability function		
Name	Function	Short description
Wave return wall		
Horizontal sliding	$Z = \frac{2}{3}\tan(\varphi)\,\Sigma V - \Sigma H$	Failure of the wave return wall due to horizontal sliding: the resulting wave impact horizontal forces ΣH exceed the friction force as a result of the weight of the wave return wall. ΣV = resulting vertical weight, friction coefficient = $\frac{2}{3}\tan(\varphi)$, in which φ = effective angle of internal friction of the soil.
Tilting	$Z = \frac{1}{6}b_f - (\Sigma M/\Sigma V)$	Failure of the wave return wall due to tilting: the resulting force $\Sigma M/\Sigma V$ is not within the core of the foundation plane. ΣM = the resulting moment of the horizontal wave impact forces with respect to the centre of the foundation plane, ΣV see sliding, b_f = width of the foundation plane.

7 MODELLING THE CALDICOT LEVELS' FLOOD DEFENCE SYSTEM AND EXPRESSING THIS MODEL INTO DATA

As is mentioned in subsection 4.2, the Caldicot Levels' flood defence system is divided into stretches and more detailed sections. For each failure mode the relevancy in terms of contribution to the probability of system failure has been determined and the weak sections have been selected according to rough indicators. The failure modes which have been taken into account are: overtopping/wave return wall, instability of the inside slope and attack of the revetment on the outside slope. The contribution of failure due to piping is assumed to be negligible as the seepage length is large at all locations along the Caldicot Levels' flood defences. The main obstacles in the data requirements are the statistical models of the hydraulic boundary conditions, the numerical models of the local water levels and the general statistical data availability. In case of the Severn Estuary a model of the local water levels has been set up with Mike11 based on limited information with respect to: geometry of the estuary and the actual occurring water levels which can serve to calibrate and validate the model. Part of the applied network can be found in Figure 2. Moreover, information about statistics did not appear in the form required for PCRing required form. In case of the River Usk a numerical model of the local water levels is available in Mike11, though only limited discharge statistics were available.

8 RESULTS OF THE CALCULATION OF THE ANNUAL PROBABILITY OF FLOODING, PRESENT AND IMPROVED SYSTEM

The calculations of the annual probability of flooding of the Caldicot Levels' flood defence system result in:

– Annual probabilities of failure and reliability indices β of the selected sections (see Figure 5).
– Coefficients of influence, or α-values.
– The total annual system's probability of flooding due to one failure mode and the accompanying weakest link in the system (see Table 2).
– The total annual system's probability of flooding (see Table 2).

The dominating failure mode turns out to be overtopping (see Table 2). The weak areas which result from the calculations correspond with the more severely attacked areas in the past storms.

The coefficients of influence point out that the uncertainty associated with in the first place the water levels and in the second place the wind speed and wind direction, contribute most to the total probability of failure. From this information the main reasons causing the above mentioned areas to be weak are derived: a low crest level in combination with the orientation of the embankment with respect to the south westerly wind directions. These wind directions are related to high wind speeds and large fetches and are therefore associated with high levels of wind set up and more severe local wave conditions.

The annual probability of failure of the wave return wall is determined by failure due to tilting and is relatively high (see Table 2). Because of this high probability, the assumption that the complete embankment fails if the wave return wall fails is not justified in this case. Therefore, based on these results the actual probability of failure is expected to be a combination between failure of the embankment with the influence of the wave return wall on wave overtopping and failure of the embankment without a wave return wall on the crest (see Figure 4, top). In Figure 5 the former scenario is referred as "improved, no failure w.r.w.", whilst the latter scenario is referred as "improved, no w.r.w. present on crest".

As overtopping is the dominating failure mode, in Figure 5 the reliability indices in connection to failure due to overtopping of the selected sections are given for the present and improved flood defence system.

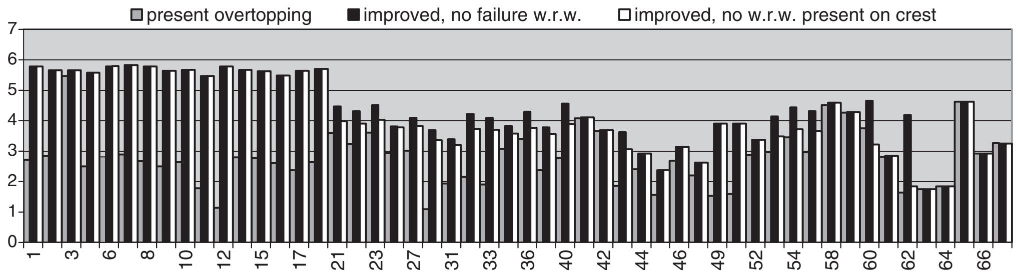

Figure 5. Reliability indices of failure due to overtopping of the present flood defence system and the improved flood defence system. For the improved flood defence system the reliability indices of embankments with and without the influence of the wave return wall on the overtopping discharges are included. Below the flood defence components and the corresponding section numbers are given.

Section no. 1 t/m 19 and no. 49 t/m 52 = embankment without additional structures
Section no. 20 t/m 48 and no. 53 t/m 57 = embankment with wave return wall
Section no. 41 and 42 = high grounds with masonry wall facing
Section no. 58 t/m 62 = raised grounds along the Severn Estuary
Section no. 62 t/m 67 = raised grounds along the river Usk
Section no. 68 t/m 78 = Usk river banks (not included in the plot)

Table 2. Results from the calculations of the annual probability of flooding of the Caldicot Levels' flood defence system in its present and improved form.

	Overtopping			Instability of the inside slope			Attack of the revetment on the outside slope			Total flood defence system		
	Weakest link		Total	Weakest link		Total	Weakest link		Total	Weakest	Total	
	No.	β	β	No.	β	β	No.	β	β	link no.	β	Pf
Present system												
With Usk	68	0.643	0.51	79	1.19	1.18	14	3.108	3.106	68	0.293	0.385
Without Usk	28	1.09	0.90							28	0.59	0.278
Improved system												
With Usk	68	0.643	0.51							68	0.532	0.297
Without Usk												
Failure w.r.w.	31	1.076	1.01									
Failure embankment with effect w.r.w. on overtopping	63	1.75	1.67									
Failure embankment without w.r.w.	63	1.75	1.67	46	3.73	3.73	29	4.5	4.36	63	1.568	0.584 $*10^{-1}$

w.r.w. = wave return wall.

Figure 5 points out that the planned improvements are unbalanced:

– Sections 1 to 20 are much improved compared to the sections with wave return wall, 21 to 40, 43 to 57, 60 and 62.
– The latter mentioned sections are moderately improved, moreover their reliability indices are very irregular.
– Table 2 points out that the sections along the Usk provide the weakest link. These sections are not improved at all.
– Without considering the sections of the river Usk, section 63 turns out to be the weakest link: this is one of the sections for which no improvement is planned.

9 CONCLUSIONS AND PRACTICAL IMPLICATIONS

9.1 *Conclusions*

The study has demonstrated how reliability analysis of a flood defence system identifies defence sections and system components that make the greatest contribution to flood risk. This information can then be used to target inspection, maintenance and upgade activities. The combination of probabilistic analysis of the flood defence system with quantified analysis of potential impacts of flooding in the zone protected by the defences provides a quantified estimate of flood risk, which can be used to justify and optimize economic investment in flood defence improvements.

In order to apply the Dutch methodology to the UK, a new failure mechanism relating to failure of the wave return wall had to be introduced into the PC-Ring program. Moreover, as is often the case for the complex failure of flood defence dikes, this new mechanism interacts with other mechanisms during the failure process. Combining separate mechanisms with logical OR gates is a simplification. However, the mathematical relations in the program are suitable. Furthermore, even though the Caldicot site was relatively well provided with data but UK standards, there was still not all of the data that would ideally be necessary for application of PC-Ring.

The study has highlighted some of the difference between flood defence systems in the UK and the Netherlands (see also Hall et al. 2000) and the implications for quantified risk analysis. There are 35,000 km of flood defences in the UK ranging from low earth embankments protecting just a few fields to the Thames Barrier protecting central London. Because of this diversity, a range of appropriate methods are required for risk analysis that are suited to the potential severity of the consequences of flooding and the available information. All of these methods should be risk-based in some sense, the intention being that risk should form the basis of decision making at all levels in the UK, from national policy decisions, regional strategic plans, to project specific appraisal, design, operation and maintenance decisions. The detailed reliability methods being promoted in the Netherlands and implemented in PC-Ring are best suited to the design and appraisal of, by UK standards, relatively large and highly engineered flood defence systems. Even for these important systems, the study described in this paper has demonstrated that some adaptation of the Dutch reliability methods and additional data collection is inevitable.

9.2 *Practical implications*

Recommendations with respect to possible adaptations of the Dutch methods follow from this study:

- Whether a "tailor-made" set up, such as in PC-Ring, or a "one-size-fits-all" set up of reliability software is desired in the UK. The tailor-made set up is based on implementing all possible failure modes in the program code, whereas the one-size-fits-all set up is based on flexibly entering the reliability functions, statistical data and the desired mathematical relations between the reliability functions. A number of typical systems can be set up default in the program, but are easier to adjust.
- With respect to models which are for instance applied in order to calculate overtopping discharges, it is recommended to choose models with an as wide application range as possible so that the results are comparable across different types of flood defences and flood defence systems.
- It is recommended to investigate whether the model which is applied in PC-Ring to transfer the hydraulic boundary conditions from a set of basic random variables to local conditions by using models like Mike11, Sobek, etc., can be applied to other numerical models, which are used e.g. in calculations with respect to other flood defence types than dikes. Moreover, this model should also be compared with currently applied joint probability methods in the UK taking into account the quality and laboriousness of both models.
- Considering the often rather low data availability in the UK, an efficient time-saving method to select the weak areas may be beneficial. To this end an approach similar to the one which is described in 4.2 could serve after adaptation to the desired risk-based method in the UK.

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