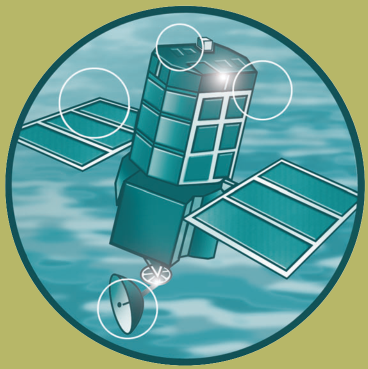
Joint Defra/EA Flood and Coastal Erosion Risk Management R&D Programme

Performance and Reliability of Flood and Coastal Defences

R&D Technical Report FD2318/TR1



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Performance and Reliability of Flood and Coastal Defences

R&D Technical Report FD2318/TR 1

Produced: August 2007

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Statement of use

This document provides information for Defra and Environment Agency Staff, researchers and consultants about the research project “Performance and Reliability of Flood and Coastal Defence Structures” and constitutes an R&D output from the joint Defra / Environment Agency Flood and Coastal Erosion R&D Programme, Modelling and Risk Theme. TR1 provides clear guidance on developing and using fragility curves for risk assessment. TR2 is a more in-depth treatment with specific interest for those developing new fragility curves.

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Preface

This document reports the findings of research into the “Performance and reliability of flood and coastal defences”- Phase I” - Project FD2318 in the Risk Theme of the Joint Defra/EA Flood and Coastal Erosion Risk Management R&D Programme. This project has explored ways to assess the performance and reliability of flood and coastal defences in order to make better assessments of risk. It directly supports Defra and Environment Agency policies, strategies and new decision-making tools for flood and coastal risk management. In particular:

- it provides information to assess the effectiveness of flood defences in reducing risk
- it provides information to support decision-making on how to manage the performance of flood defences
- it provides methods to help to assess flood and erosion risk including performance of defences under extreme loads.

The project reviewed a range of methods for assessing the reliability of different types of defences, including their deterioration in time. It then focussed on developing practical methods for assessing reliability[1] using ‘fragility curves’. A fragility curve summarises information about the probability of failure of an engineering system such as a flood defence, in response to a specific range of loads (e.g. high water levels or waves). This report presents the main findings of the project including the methodology developed to construct fragility curves.

This report is aimed at those carrying out, or with an interest in, flood and coastal risk assessment. It describes the scientific and practical basis for fragility curves, and their role in the risk and performance based management framework (Ref: FD2318/TR1). The report is intended to inform and assist those involved with managing flood and coastal defences, and assessing risk associated with flood defence structures and systems. FD2318/TR2 compliments this report by providing a more in-depth technical background including the mathematical equations of failure processes that were used for fragility calculation.

[1] Reliability is the complement of failure probability. For example a defence may have a reliability of 0.99 or a failure probability of 0.01 per year - the meaning is the same

Executive summary

This report summarises key findings of R&D project FD2318, ’Performance and Reliability of Flood and Coastal Defences’. The objectives of the overall study were:

- To explore the available approaches to characterising the reliability of flood and coastal defences
- To develop scientifically justified fragility curves capturing information about the performance of structures under a variety of loading conditions.
- To provide clear guidance on developing and using fragility curves for reliability analysis of linear defences.

This project has investigated and considered how the concept of fragility can be practically applied to the assessment of flood and coastal defence assets. It looked at how other industries use ‘fragility’ and then developed a technical basis for its application in flood and coastal defence management.

The concept of fragility expresses the probability of failure given a range of loading conditions and summarises the information about the reliability of a flood or coastal defence. Useful by-products are knowledge about the most prominent failure modes (in detailed level risk assessments) and the characteristics of the structure that contribute most to failure of the defence. Moreover, the concept of fragility allows the combination of conditional probabilities of failure with complex consequence of failure scenarios.

The report aims to assist:

- Those involved with managing flood and coastal defences, and assessing risk associated with flood defence structures and systems.
- The further development of Defra and Environment Agency policies, strategies and new decision-making tools for flood and coastal risk management.

Please note that this is a research and development (R&D) output and no part of this report constitutes formal Agency or Defra policy or process.

This report is composed of two volumes. Volume one (TR 1) states the conceptual reasoning behind the application of the fragility curve method which is discussed. A step by step guide to the construction of fragility curves is provided along with additional guidance and includes generic fragility curves. Volume two (TR 2) provides more in-depth technical treatment including the reliability functions that have been used. Chapter one introduces the RASP (Risk Assessment of flood and coastal defence for Strategic Planning) defence classifications and the approach to fragility used for National Flood Risk Assessment (NaFRA). Chapter two shows how fragility curves were created for the High Level Plus method of flood risk assessment and Chapter 3 introduces a more detailed approach to capture indicative failure modes in fragility.

Acknowledgements

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1. Introduction

1.1 Introduction

In the past, the provision of flood and coastal defence was sometimes seen as a distinct set of activities or functions (such as capital projects, implementation of flood warning systems, assessment of land use planning applications), but now it is recognised that these activities must be regarded as part of a coherent flood and coastal risk management activity. This more integrated approach was signalled in the ICE's report 'Learning to Live with Rivers' (2001), and the changes needed were described in more detail in the Environment Agency's Strategy for Flood Risk Management (2003a). This shift can and should lead to more efficient flood and coastal defence, but it also presents challenges. Key challenges include:

- assessing flood and coastal erosion risk
- assessing the performance of flood and coastal defence systems under a range of conditions, and
- understanding the benefits (in terms of risk reduction) of various management interventions available.

In order to help the flood and coastal erosion risk management community meet these challenges, this report describes tools and techniques relating to the structural performance of flood and coastal defences. These tools help to assess the reliability of a range of structures under a range of (extreme) loads.

Fragility[2] curves have already been used for National Flood Risk Assessment (NaFRA) and in Flood Risk Appraisal for Strategic Planning. The Flood Risk Management Research Consortium (Research Area 4 – Infrastructure) is adding to and enhancing this work in specific areas such as geotechnical stability, detailed failure mode analysis, systems based analysis and visual condition assessment (see http://www.floodrisk.org.uk/ for more details). Work under the FLOODsite Project also meshes with these initiatives by integrating supporting European research in areas such as defence failure modes, breach initiation and formation, quantifying and handling uncertainty, and in the development of integrated risk management strategies and tools (see http://www.floodsite.net/ for further information).

1.1.1 Objectives of the report

The overall objectives of this project were:

- To establish:
  - the available approaches to characterising the performance and reliability of flood and coastal defences in other industries and other countries
  - the main failure processes associated with the main flood and coastal defence types

[2] The *Fragility* of a structure is defined as 'the probability of failure conditional on a specific loading' (Casciati and Faravelli, 1991). See section 3.1.2 for background to the concept.

  - the appropriateness of the concept of fragility to capture those main failure processes and to inform decision-making .
- To develop scientifically based fragility curves capturing information about the performance of structures under a variety of loading conditions.
- To provide clear guidance on the concepts of characterising defence performance, including the presentation of existing knowledge on the performance of all types of linear defences.

This report gives guidance on how to construct fragility for a single dominant failure mode. The associated Technical Report FD2318/TR2 extends this to discuss analysis of multiple failure modes.

Firstly, the investigation into the existing knowledge on the main failure modes and deterioration processes of the main structure types is summarised. This investigation partly consists of a desk study of process-based models and partly builds on interviews with experts covering a variety of coastal and flood risk management issues. An overview of failure and deterioration processes of the main structure types and their indicators are given in tabular form. In addition, the most prominent failure processes for each structure type are presented.

Secondly, the concept of fragility is introduced. Existing approaches to fragility calculation are discussed. The most suitable approach is chosen to characterise fragility. Different views on fragility are discussed and the concept of fragility is evaluated, both in terms of its role in coastal and flood risk management, and in the practicality of constructing fragility for each structure type.
Thirdly, guidelines are provided on how to build fragility curves for prominent failure modes. This procedure is applied to the main structure types and reported in TR2 accompanying this guidance document. In TR 2 the equations, the decisions about statistical representations, and the data requirements are included. The approach developed in this project is fine-tuned to situations with low data availability. The models presented in TR2 provide a basis for future improvements of the fragility curves when more data becomes available and for more detailed risk assessments.

Any knowledge gaps in this methodology have been identified where apparent and recommendations made for further development.

1.1.2 Structure and Readership of the report

Chapter one is a basic introduction to existing risk analysis and assessment of flood and coastal defences. Chapter two outlines existing knowledge on the performance and reliability of flood and coastal defences by defence type and failure mode. Chapter three defines fragility curves, their role in risk assessment, existing uses, and their applicability and use in flood management. Chapter four describes the methodology for constructing fragility curves and provides examples of application. Chapter five outlines the main conclusions and gives some recommendations for the application of the Fragility Curve method

This guidance document intends to inform and assist:

- Those involved with managing flood and coastal defences and assessing risk associated with flood defence structures and systems. (Please note that this is a research and development (R&D) output and no part of this report constitutes formal Agency or Defra policy or process.)
- The further development of Defra and Environment Agency policies, strategies and new decision-making tools for flood and coastal risk management.

The use of fragility is valuable to analysts, practitioners, managers, planners and strategists as it provides a common approach to assessing the performance and reliability of flood defences under load, which is a valuable tool in flood and coastal defence management decision-making throughout the tiered approach to planning flood and coastal erosion management measures, as shown in Figure1.

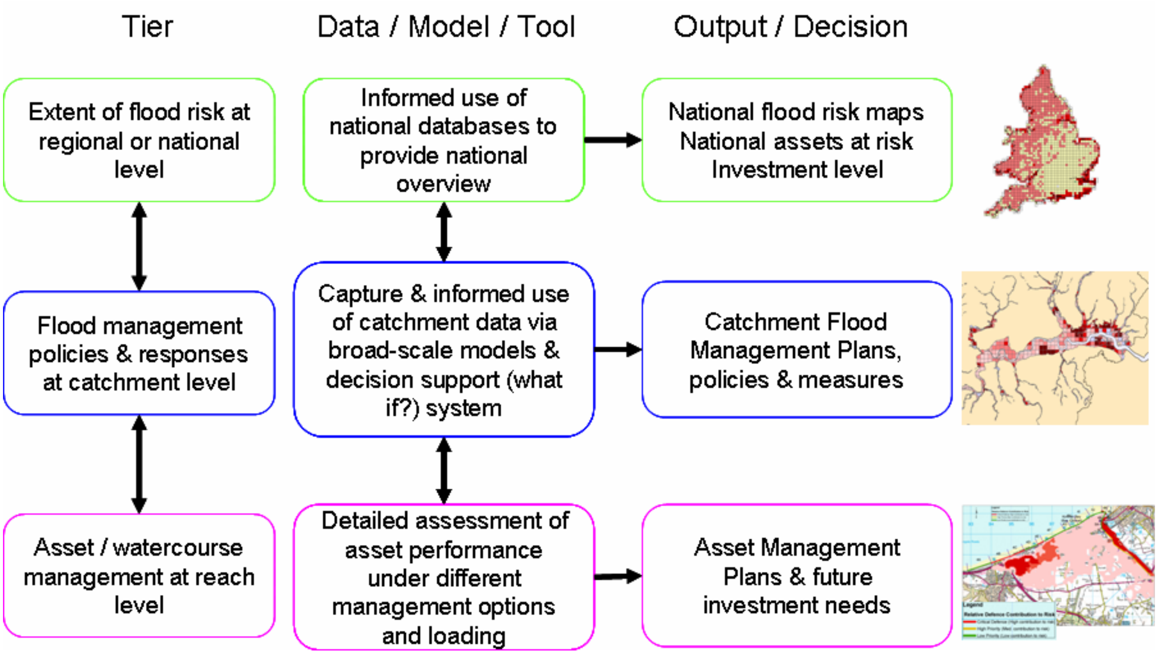


Figure 1 The tiered approach to planning flood management measures in the UK

Flood and coastal defence managers are engaged in an ongoing cycle of monitoring, evaluation, decision-making and action in order to optimise the risks and costs associated with flood and coastal management systems. This continuous cycle of actions is illustrated in Figure 2 below and involves:

- The assessment of the risks associated with a flood and coastal defence system that need to be reduced
- The identification of an optimum programme of management interventions (performance management) to achieve a particular outcome – some desirable reduction in risk
- The implementation and use of that programme
- Reviewing and checking (performance review)

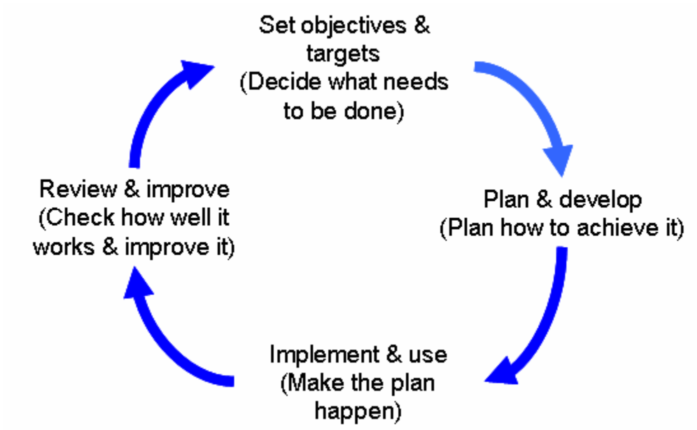


Figure 2 The Asset Management Cycle

The acquisition of information about the state of the flood or coastal defence system and, on the basis of that information, making resource allocation decisions, is part of the daily activities of flood and coastal defence managers.

The management of assets is a particularly important part of the overall performance management process. Performance-based asset management of the system must consider:

- The whole life cycle of systems (to secure the greatest return on investment)
- Maintenance, renewal, and replacement options with the goal of optimising the performance and effectiveness of the assets.

The objective therefore must be to assess performance on a continuous basis and at appropriate times, maintenance, renewal or replacement interventions initiated to restore the original performance capability, and to extend or re-initiate the residual life of the system or asset. For such a process, it is essential that the monitoring involves a process of condition characterisation which is unambiguously related to performance levels. One useful way of characterising condition is by the application of fragility methodology to gauge the performance and reliability of a system or asset.

Monitoring of existing assets is only part of the issue. The application of fragility may also have a role to play in the design of systems and structures and in the planning of remedial works. Future developments would no doubt benefit from the analysis of the potential performance and reliability of a system or structure before being undertaken. The application of fragility methodology also compliments other tools such as cost-benefit analysis, environmental impact assessment, whole life costing, and of course, flood risk assessment.

1.2 Flood Risk Management in the UK- An overview

To understand where fragility ‘fits in’ to flood risk management it is necessary to appreciate the existing and developing approach to flood management in the UK.

Flood risk assessments in the UK are based on the source-pathway-receptor-consequence (s-p-r-c) model (Sayers *et al*, 2002, ICE, 2001, HR Wallingford, 2002, Defra/EA, 2002) (see Figure 3). In flood risk assessments, for example, the source in the s-p-r-c model is the hydraulic load such as water level or waves. Overtopping or breach of the defence can represent the pathway or the response of the defence to different hydraulic loading conditions. 'Receptors' include people, property, infrastructure and the environment located in the defended area that can be affected by flooding. Finally, the consequence relates to the damage caused by the floods[3] to the receptors in the floodplain.

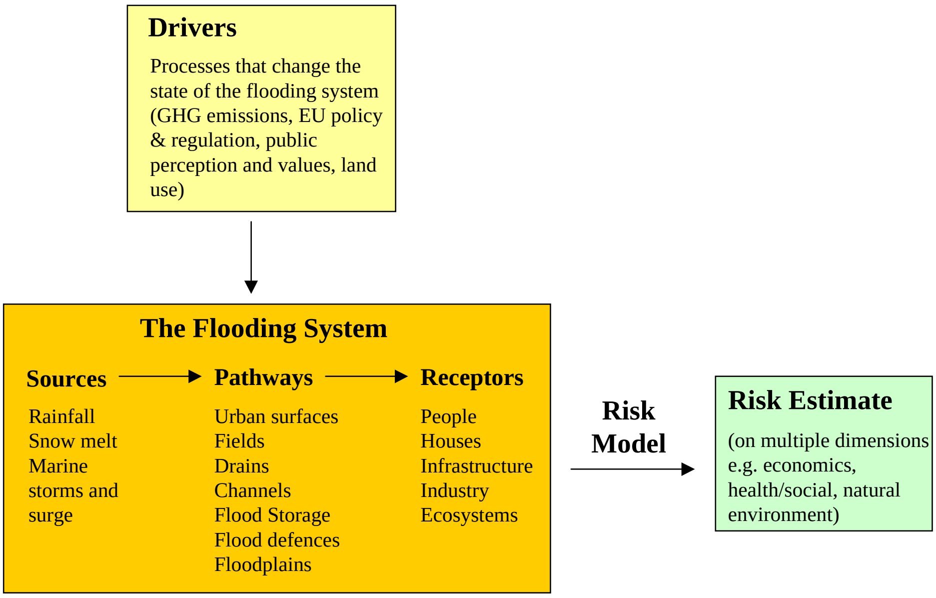


Figure 3 Source-Pathway-Receptor model, Drivers and Risk

Considering the s-p-r-c model for risk assessments there is a need to determine the consequences given a number of different possible responses of the pathway, which in turn are dependent upon different source conditions. The generally applied definition of risk is that it equals the likelihood of an event, combined with the undesired consequences of that event.

Recently, significant advances have been achieved in understanding the concepts underpinning a risk-based approach to flood management. For example the Defra / Environment Agency R&D Report, FD2302/TR1, entitled *Risk, Performance and uncertainty in Flood and Coastal Defence – A Review* (Defra/Environment Agency, 2002), built on the "Source / Pathways or Barrier / Receptor" approach to risk management (see Figure 1). It established the concept of a tiered approach to risk-based decision-making with an interactive suite of tools, models and data addressing the national, catchment / coastal cell, and local (i.e. asset management and river reach) levels. This concept is now well established and accepted and has been widely used in National Flood Risk Assessment, National Appraisals of Defence Needs and Costs, and most notably and publicly, in the Foresight Future Flooding project (Evans

[3] Note: 'Floods' often used but methods apply equally to coastal defences.

et.al,2004). Within the context of tiered flood risk management, a Performance-based Asset Management System (PAMS) (Environment Agency, 2004c) is now being developed to provide an improved approach to managing fluvial and coastal defences at the local level.

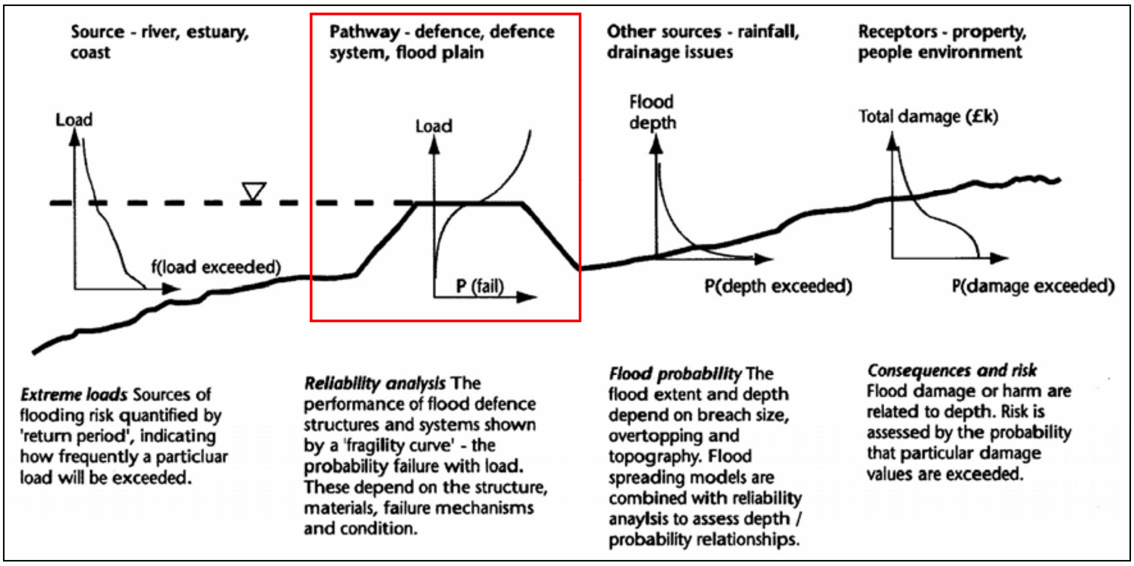


Figure 4 Source / Pathway or Barrier / Receptor / Consequence model for flood risk

PAMS will apply to all flood defence assets including embankments, walls, and rivers (conveyance), and tidal and sea defences. It will also apply to other structures which have a primary flood defence function such as gates, sluices and pumps.

The application of fragility in the s-p-r-c model is clear – as denoted by the red box in figure 4. The fragility method fills a former gap in the ability to model the flooding system and analyse it with any consistency.

In support of a common approach to risk and risk management across all of its flood management functions, the Environment Agency is currently developing a series of tools to support specific decisions in each of its main business functions. PAMS is a key element in this overall framework.

In recognition of this overall framework, PAMS will take its policy lead from higher level tools (such as CFMP/SMPs and Flood Defence Strategies) and then aim to ensure that assets are managed to meet specific policies or measures for each location as set out in regional management plans. Where these policies include management or improvement of assets on their current alignment (or similar), PAMS will ensure that these are implemented (in the best way) to ensure the overall policies (as encoded in SMP / CFMP) are met efficiently and effectively. It will also be important that the added-value provided by PAMS, through detailed site specific analysis, is able to be fed back to the higher level tools to inform future decisions.

It may also be feasible to apply fragility to urban drainage systems, however, these are complex due to the large number of potential interactions with other flooding and failure mechanisms. One of the main problems is estimating probabilities of failure for these mechanisms. This area is the subject of ongoing research which proposes to develop fragility curves that estimate the functionality of each mechanism to different loading conditions.

1.3 Risk analysis and performance evaluation - different levels of detail

To ensure appropriateness, different reliability analysis methodologies can be used for different stages of risk analysis and performance evaluation. According to recent R&D into performance evaluation, performance appraisal consists of three main steps:

- Objective setting
- Condition/state assessment
- Performance assessment.

The condition/state assessment can be subdivided into a number of levels of detail ranging from superficial visual condition assessment (inspection) to more detailed condition assessment involving measurements as shown in Figure 5.

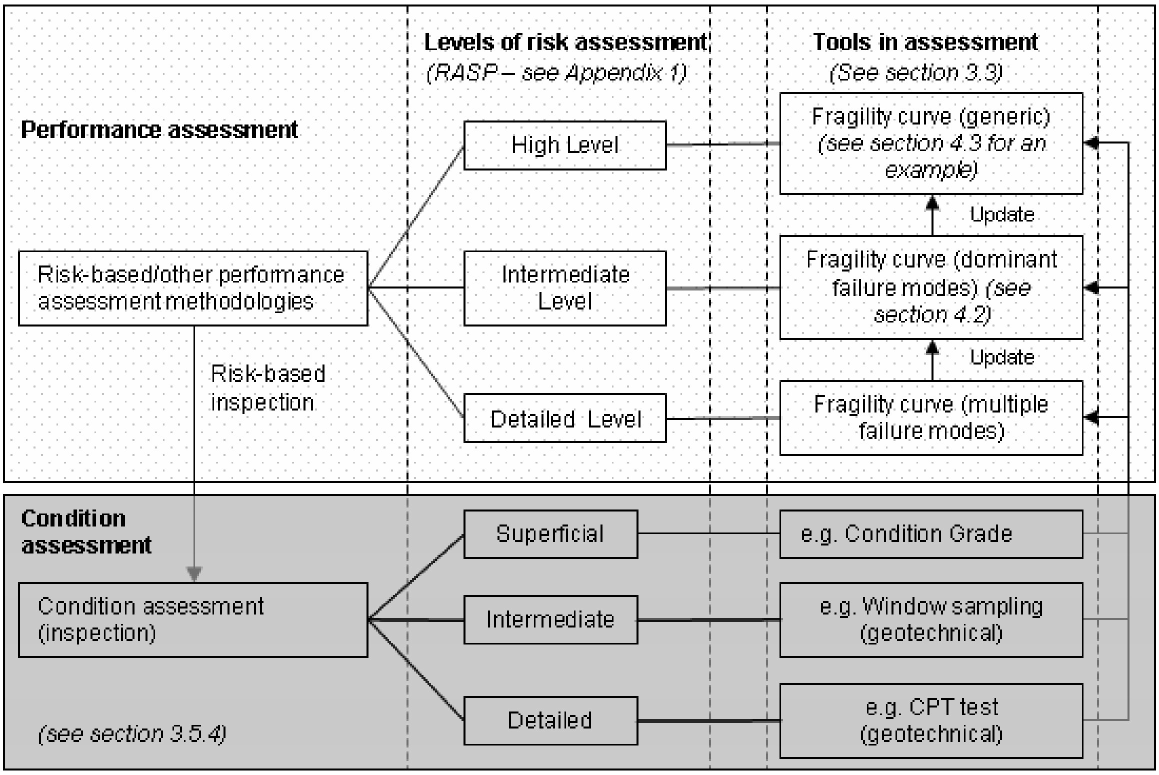


Figure 5 Tiered performance assessment and inspection methods and updating

The performance assessment can be subdivided in a number of different levels as well. In the future, part of the performance assessment will be risk-based. Risk assessment for Flood and Coastal Defence for Strategic Planning (RASP) (HR Wallingford, 2002) introduced a tiered risk assessment methodology consisting of;

- a ‘high level method’, informing national level decision making,
- an intermediate level, informing regional decision making, and
- a detailed level methodology, informing decision making on the level of a flood defence system.

These tiers of risk assessment can also be compared to the increasing detail in the design of new (systems of) structures: feasibility stage, preliminary design and detailed design for construction. As with tiered flood and coastal risk assessments, these tiers inform different decisions, building on increasingly detailed data sources and underpinning process-based models. For example, broad-scale risk assessments often require delivery of results quickly with limited investment resources. Hence, in order to meet those targets, the effort in data collection is limited and the representation of failure processes involved is simplified. A similar situation can be recognised in other engineering industries (see Dekker, 1996 and Dekker and Scarf, 1998). Section 3.3 describes the application of fragility in the different tiers of flood and coastal erosion risk assessment in more detail

As Figure 5 shows, assessment tools are needed to ‘map’ or translate condition grade and other structural information into assessments of performance and risk. This research has shown that fragility curves are a key aid in this process.

‘Generic’ fragility curves are used in High Level Risk Assessments such as NaFRA. Their development and application are described in Chapter 2 of the second volume of this report (TR2), and the subsequent chapter introduces fragility curves for the more detailed levels of risk assessment using dominant or indicative failure modes. More work and research is recommended to further refine the fragility methodology and to encompass multiple failure modes.

2. Existing knowledge on the performance and reliability of flood defences

The performance of a flood or coastal defence is assessed by its relative success when evaluated against the aims or objectives of its function. The ways in which a defence structure fails to fulfil its function are referred to as failure modes. A proper function definition is therefore at the root of a meaningful performance assessment. Reliability is a measure of structural performance quantifying the failure processes of flood or coastal defences. Several kinds of reliability methods are available to describe these failure processes.

This chapter explores and summarises the knowledge about the way flood and coastal defences behave, how they are built, what forces they are exposed to, and how they might deteriorate and fail as a result. Some definitions in this context are given below.

Section 2.1 outlines the classification of defence structure types; 2.1.1 defines 'linear' defences and their loads and 2.1.2 defines 'point structures' and their functional requirements. Section 2.2 discusses failure modes, indicators of failure, deterioration and indicators of deterioration of embankments, vertical wall structures, beaches and point structures. 2.3 lists non-generic factors affecting the risk of failure.

2.1 Defence classification

Flood defences in this report are identified according to the RASP classification (according to HR Wallingford, 2004a), excluding culverts and high grounds;

Flood Defences

Fluvial	*Coastal*
Vertical Wall	Vertical Seawall
Slope or Embankment	Sloping Seawall / Dyke
High Ground	Beach
Culverts	

Generically and for the purpose of fragility, defence structures can be divided into two aspects;

1. Linear defence structures and,
2. Point structures (e.g. pumps, gates, culverts)

Coastal defences are defined as defences with a function to either protect against erosion or against flooding by the sea. Coastal defences with a function to protect against flooding are referred to as *coastal flood defences*, and coastal defences with a function to protect against erosion are referred to as *coastal protection*. Coastal protection structures are limited to man-made defences such as revetments and do not include natural protection such as cliffs.

Flood defences are defined as defences which protect against flooding by a river or the sea.

2.1.1 Linear defences

A 'linear' flood defence or coast protection structure forms a line of defence with a uniform nominal cross section. In its simplest form it consists of a structure (the main defence body) and a foundation (or bedding structure). The body of the defence or structure is the part of the defence upon which loads act. The foundation is where the structure interacts with the natural ground. The distinction between the foundation and the body of the structure however is not always clear.

The performance of a defence structure is controlled by;

- the magnitude of the loads (water level, waves, wind, traffic etc) acting on the structure
- the response of the structure to the loading
- the performance of the foundation. (The performance of flood defence structures, particularly embankments can be heavily influenced by the nature of the ground on which they are constructed.)

Although the particular nature of flood defence loadings and performance requirements has received much attention in the past, there is currently no design or performance assessment guide on how to appropriately handle these conventional performance methods in support of risk-based design and assessment. Current practice involves the use of standard codes and principles that have been developed for other uses which have been modified as necessary for flood defence assessment.

2.1.2 Point Structures (pumps and gates)

Point Structures (sometimes also referred to as 'components') such as pumps, gates, and culverts need to come into action when they are in demand - apart from reliability, failure-on-demand must also be considered. Defra/Environment Agency (2003b) defines failure-on-demand as:

> *'an event in which a system or component fails to perform its intended function for whatever reason, including but not limited to: incidents which overwhelm its design capacity, failures of systems, or components in continuous or intermittent use'.*

In terms of the probability of failure-on-demand, two types of use are considered: *intermittent use* and *emergency use*. Failure-on-demand can therefore be derived practically by establishing the fraction of time that an element does not fulfil its function (CUR, 1997). Some causes of failure-on-demand for example might be:

- due to hidden failure - the element does not operate between the time of failure and time of testing

- due to testing or maintenance activities
- due to repair or replacement activities after failure has been detected.

Extra functional requirements

When a system of defences locally has extra functional requirements in addition to its water retaining or coastal protection functions, point structures are often used: e.g. the need for a water outlet, to let ships through, etc. The need for pumps to extract water, for gates to open and close, and culverts to channel flow, leads to extra design requirements for these structures compared to linear flood defences which 'just lie there'. One of the differences is the presence of mechanical parts. These mechanical parts are more susceptible to time and use dependent processes such as corrosion or fatigue than to hydraulic load dependent processes.

These extra functional requirements can also lead to, for instance, the need for human involvement (leading to error), or obstruction of flow by debris. These can cause the failure of pumps and gates. Again, both types of failure are not necessarily determined by hydraulic load dependent processes.

If the reliability of point structures such as pumps and gates are considered in detail, it is possible to construct fragility curves. Different failure modes can be assessed by deriving a failure rate based upon empirical data. If sufficient data are available the failure rate can be determined given different loading situations. This probability of failure can be integrated with the probability of failure of the overall structure under a given a load.

As failure of a point structure does not necessarily directly lead to flooding, the objectives of the risk assessment will be served much better if the failure of the point structure is considered as part of the overall system of rivers and channels. A fragility curve can be constructed to determine the exceedance of the capacity of the total system given a certain amount of rainfall, and / or, the local exceedance of a bank of a watercourse. Such an 'overall' fragility curve will contain much more information than a fragility curve for only one point structure.

2.2 Failure modes / indicators of failure / deterioration and indicators of deterioration

Understanding failure modes is important to reliability assessment for two main reasons; the right process-based models can be applied in the application of fragility in the right circumstances and, indicators of failure modes can be included in condition assessments to elucidate the current condition of defences.

This section is divided into linear defences (2.2.1), and point structures (2.2.2). Brief descriptions of each type of defence, their nature and purpose are discussed followed by identified prominent failure modes and failure processes affecting their performance. Table 6 collates this information and Sub-section 2.2.3 summarises the dominant failure processes identified. Section 2.3 lists the non-generic factors affecting probability of failure that have been identified but not yet encompassed in the methodology.

2.2.1 Failure modes of linear defences

Possible failure modes of linear defences together with the indicators of failure and indicators of deterioration are shown in Table 6. This category includes embankments, vertical and sloping wall structures, and beaches and are discussed in detail in this section.

The performance of a defence structure is controlled by the magnitude of the applied loads (water level, waves, wind, traffic etc) on the structure, the structure's response to the loading and the performance of the foundation. The performance of flood defence structures can therefore be heavily influenced by the nature of the ground on which they are constructed. This is particularly the case for embankments which are themselves earthworks.

Of the four principal categories of flood and coastal defences described in Section 2.1, the influence of the ground on the performance of defences remains highly significant for embankments, sloping walls and vertical walls (retaining structures) and less so for beaches.

Embankments

Description and function
Embankments are essentially earthworks – usually constructed from locally sourced materials. Depending on the prevailing hydrodynamic conditions, they may have slope protection and other protection systems such as rock armour, riprap, or revetment block systems. As underlying soils can vary, site conditions often also require filter or geotextile layers to be installed to control drainage.

The purpose of a slope protection system on an embankment is to dissipate incident wave energy to prevent damage to sensitive structures, properties, facilities and other assets and environments behind the defence. In coastal environments slope protection systems are often only one part of extensive shore protection measures which might also include groyne fields and cliff stabilisation measures.

Flood embankments essentially act as low-level dams for short retention periods. For the majority of the time, the embankments are only exposed to low hydraulic heads (or none at all) and remain largely unsaturated. However, during flood or storm events embankments may need to withstand a rapid rise in water level or other loading on the outward face, along with corresponding changes to internal water pressure (and perhaps seepage) driven by higher than normal hydraulic gradients. The increase in hydraulic head on the embankment may be further exaggerated by the use of additional temporary flood protection on the crest of the embankment.

Given their apparently simple nature, the prediction of the behaviour of flood defence embankments is far from straightforward, and understanding potential breach initiation mechanisms under extreme loading is difficult. This is further compounded by the long lengths of flood defence embankment that exist to protect rivers, estuaries and coastlines, which make a comprehensive structural assessment of all embankments logistically difficult to implement. Nevertheless, knowledge about the type of material used to construct an embankment, and of the method used to construct it, does allow its performance to be analysed using principles of soil mechanics.

Construction
Many flood embankments are relatively old structures that have evolved over decades, or even centuries, from original constructions. In contrast with the modern construction of embankments for highway and dam projects using heavy earth compaction equipment, many flood defence embankments have been built using low cost traditional techniques. These traditional methods have often evolved to suit local sources of fill material which have been excavated from nearby surface deposits or retrieved from river sediments. Common techniques historically used for embankment construction include excavation from drainage ditches, and the use of dredged silt.

A review of traditional earthwork materials used to construct flood embankments (Environment Agency, 1996) found a wide range of soils and rocks used as fill material depending on the local geology and particularly the superficial deposits. As might be expected for embankments constructed along major rivers and estuaries in the southern and eastern parts of the country, alluvial clays and silts are a common source of material. In comparison, the absence or shortage of alluvial soils in North Wales has led to the use of Anglian sand, shingle, or even slate waste. The use of such a wide range of materials has implications for the performance of embankments and in particular the susceptibility to different failure mechanisms. For example, the use of sand and shingle for the construction of flood embankments at several estuaries along the west coast of Wales has resulted in high seepage rates that cause flooding of adjacent roads. In contrast, the use of highly plastic clays in the Anglian region has led to fine fissuring, which has increased internal seepage and reduced resistance to erosion from overtopping.

In addition to providing a source of fill material, superficial deposits act as the founding strata for flood embankments and can strongly influence slope stability as well as sub-surface seepage. The drying or settlement of soft organic clays can lead to considerable settlement and cracking of flood defence embankments. In comparison, continuous and especially isolated buried channels of coarse-grained deposits can cause excessive sub-surface seepage, which can lead to piping and embankment collapse.

Deterioration and Failure processes affecting the performance of Flood Defence Embankments

Embankment body and founding strata.
Although there are several geotechnical factors that can affect the performance of a flood defence embankment, the individual factors can be divided into two main groups depending on whether the hazard develops in the founding strata

or the embankment itself. A simple guide to the range of hazards and risks that can occur is shown in Table 1. The table is based on a general understanding of geotechnical processes involved with embankment performance supported by case histories about embankment failures during the last 50 years, including the 1953 North Sea Floods (Environment Agency 2003c). This assessment of the geotechnical factors affecting the performance of embankments show that hazards stemming from the founding strata could potentially result in the following:

- excessive settlement
- deep seated slope instability
- large scale lateral movement / sliding
- excessive under seepage and piping
- deep rotational failure

In comparison, the hazards associated with the embankment itself are identified as follows:

- surface or toe erosion (outward and inward faces and crest)
- excessive internal seepage and piping
- shallow slope instability

Some of these hazards are short term, such as deep seated instability due to construction on soft clays. Others are long term, for example, fine fissuring resulting in excessive internal seepage, which can lead to internal erosion or instability of the inward face.

Another factor is the reduction in effective crest level by rutting, erosion and settlement due to frequent use for access by vehicles, people and animals.

Slope Protection systems
A slope protection system must be able to resist wave attack as well as the erosive action of groundwater and surface water. It follows that any slope protection system must be designed to satisfy geotechnical as well as hydraulic criteria. Other issues which need to be considered when designing a slope protection system are hydraulic performance, durability, flexibility, constructability, maintainability, and ecological and visual impacts.

As a wave approaches a soil slope, the upward movement behind the breaking wave disturbs the ground surface and draws finer soil particles away from the slope. The up-rush and down-rush of water shear the surface and cause erosion. When a plunging wave hits the slope, it causes local increases in pore-water pressure which can eventually lead to local slope instability. It can also have the effect of liquefying the soil and allowing it to be washed away in the subsequent back-swash of water down the slope. The effect of a number of waves is to drive up the net phreatic surface, increasing peak outflow pressures/velocities

The purpose of the slope protection system is to insulate the ground from the destructive action of incident waves. However, the system itself must be stable in the prevalent wave conditions. In particular, the size and type of components which make up the armour or cover layer have to be sized on the basis of the anticipated severity of the wave attack.

A slope protection system can also be attacked from behind as a result of groundwater or surface water flows. A large difference between the groundwater level and sea level can exist if the rate of drainage from the land cannot keep pace with the fall of the tide. This situation is called ‘tidal lag’. The resulting seepage pressures can have an adverse effect on the stability of a slope. They can also cause finer particles of soil to be washed out from the natural soil which constitutes the slope.

The flow of water through soil can cause the migration of fine soil particles through that soil. This process of internal erosion may lead to the formation of unstable voids which may eventually result in collapse and surface settlement. The term ‘filtration’ when used in a civil engineering context is used to describe the process of controlling or preventing the movement of soil particles. For a filtration process to be effective, a stable interface between the base soil and the filter layer needs to be established. This process is not instantaneous - some movement of soil particles is required before a stable interface can be created. As a result, the base soil in contact with the filter gradually becomes coarser, but as the filter becomes clogged with fines a transition zone is formed. There is clearly a need for compatibility between the base soil and the filter (whether it be a granular filter or a geotextile one); if the filter material is too coarse a stable interface can never be established. However, once a stable interface has been established, it will effectively inhibit the migration of soil particles unless the hydraulic gradient becomes excessive or if cyclic flow conditions occur.

The above process requires one-directional flow. For seawalls however, the flow is usually bi-directional (because of tides and waves). This reversal of the flow direction can cause a breakdown of the arching which is a necessary component of filtration. Thus a stable interface can be difficult to establish in these situations. A filter’s vulnerability to being broken down by wave or tide action increases with proximity to the water. A geotextile filter placed beneath a thin armour layer is more vulnerable to this process than a thick granular filter layer.

(Geotechnical Control Office, 1993), the two principal design requirements for filters are:

1. Retention – There must be no excessive loss of fine particles from the base soil during the service life of the engineering structure.

2. Permeability – The permeability of the drainage system must reach a steady state value which is sufficiently high for water to flow freely and which must not reduce with time.

Table 1 Geotechnical Factors Affecting the Performance of Flood Embankments *(from Environment Agency, 2003c)*

Element	Hazard	Field Observations	Risk	Geotechnical Process	Ground Conditions to be Considered/ Investigated
Founding strata	Settlement	Low crest levels	Low crest levels leading to overtopping	Consolidation (dissipation of excess pore pressures).	Consolidation and compression characteristics of underlying soils. Secondary consolidation and creep of soils and fill. Differences in horizontal and vertical permeability of foundation material.
	Deep Rotational Failure	Tension cracks on embankment crest. Settlement of part of crest. Lateral displacement of embankment toe. Heave of ground in front of toe.	Catastrophic failure of embankment	Shear failure during construction or embankment raising	Shear strength of fill and foundation soils, in particular undrained shear strength of clays. Possible longer term gain in strength due to consolidation.
	Translational Sliding	Distortion of embankment crest leading to bulging along inward face	Catastrophic failure of embankment	Lateral hydraulic force exceeds shear strength of founding strata along base of embankment or desiccation of organic fill leading to a reduction in deadweight	Shear strength of soft clays and organic soils directly beneath the embankment. Desiccation of peat and organic fills leading to a reduction in deadweight
	Seepage and piping	Seepage or ponding of water in front of embankment.	Seepage causing internal erosion and piping	Under-flow of flood water leading to erosion and slope instability.	Presence of highly permeable strata beneath embankment either leading to excessive seepage
	Uplift Pressures	Heave of embankment toe.	High pore pressures causing instability.	Build up of uplift pressures in confined permeable strata due to hydraulic continuity with flood water.	Presence of highly permeable strata beneath embankment either leading to build up of pore pressures due to confinement.
Embankmen t Structure	Shallow Slope instability	Shallow translational slumping or slippage of embankment side slopes Possible tension cracks on embankment crest, settlement of crest, lateral displacement of embankment toe or heave of ground in front of toe.	Damage to outward and inward faces of embankment leading to a loss of integrity or a reduced resistance to seepage or overtopping.	Instability during rapid draw-down after flood event. Longer term slippage of slopes due to pore pressure equilibrium and/or reduction in soil suction Erosion of toe along outward face due to river migration	Compaction of fill material in relation to moisture content. Build up of pore pressures after lengthy period of flooding resulting in saturation of fill material or leading to uplift. Swelling of over consolidated clay fill leading to shallow slips (1 to 2 m depth). Reduction in soil suction pressures in partially saturated soils following infiltration of rain and/or flood waters.
	Internal seepage	Cracking within embankment body. Visible seepage on inward face of embankment, particularly during “bank full” conditions. Local variations in growth of vegetation	Washout of embankment fill material leading to piping and eventually breach	Excessive seepage caused by desiccation and fine fissuring. Excessive seepage due to highly permeable fill material.	Shrinkage of medium and highly plastic clay leading to fine fissuring. Excessive seepage through coarse-grained fill leading to piping at critical hydraulic gradients.
	Erosion of outward face and toe	Bare soil, loss of material visible Undercutting at base of slope	Increased risk of seepage or instability	Erosion of outward face and toe due to river migration.	Shear strength and grading of embankment material. Geomorphological assessment of long term river migration.
	Erosion of inward face	Bare soil, loss of vegetation	Reduced resistance to overtopping	Erosion of inward face due to over flow	Selection of suitable topography, topsoil and vegetation. Possible use of geotextiles.

For granular (as opposed to geotextile) filters a third criterion of segregation is applied. The principle is that the filter should not become segregated or contaminated with other soils prior to, during, or after installation.

Runoff of surface water (which might be due to wave overtopping or inadequate drainage) is another cause of slope erosion.

The method of preventing internal erosion or surface erosion due to runoff must allow for the fact that the vulnerable section of the embankment will change position, depending upon the groundwater level and the tidal level. The effect of a layered slope protection system on drainage and hence the performance of the structure depends crucially on the relative permeabilities of the various layers involved.

Table 2 Prominent failure modes for embankments / sloping seawalls and for slope protection systems.

Embankment / sloping seawall
• Erosion of crest and outside face leading to breach following overflow or wave overtopping (possibly induced by settlement)
• Piping, excessive seepage, breach or collapse following deterioration due to animal infestation
• Breach following failure of foreign objects or weak spots caused by their presence
• Rotational and/or translational sliding failure due to exceedance of soil shear strength
• Structural failure following vandalism
• Toe erosion/foundation failure
• Failure of slope drainage
• Damage by boats and barges
• Structural failure of inflexible or rigid revetments placed on dynamic watercourses/coastlines

Vertical Wall Structures

Description and function

There are two main types of retaining structures generally used for flood protection or shore protection:

- Gravity walls - in which stability is achieved mainly from the weight of the structure itself.
- Embedded structures - in which stability is derived from passive resistance of the soil in front of the embedded length, and sometimes with external support.

Examples of different types of retaining structures used for shore protection or flood defence are given in the CIRIA report “Seawall Design” by Thomas & Hall, (1992). Other examples are given in Stickland & Haken (1986) "Seawalls, Survey of Performance and Design Practice", BS8002 (1994), BS6349:Part 2 (1988), “Revetment systems against wave attack – a design manual” by

McConnell (1998), Hong Kong Geoguide 1 (1994), and the British Steel Piling Handbook (1997).

Designed to support the ground with a near vertical front face, retaining walls support the ground permanently, but often they are also designed to support transient loads such as vehicular traffic or floods. They are usually designed in accordance with rigid structural and geotechnical codes which provide relatively little guidance on wave induced loads. In contrast to retaining walls, flood walls project from the ground, and are only required to resist lateral pressures when flooded.

With retaining walls, horizontal movement at the top of the wall is often of great importance (a serviceability limit state requirement). However, movement of the top of a flood wall may not be important as long as it does not fail (an ultimate limit state requirement) or lead to the long term deterioration of the structure.

Construction
Although commonly constructed of concrete, currently there is no specific guidance relating to the design of flood walls. If retaining wall design procedures are used, flood walls can be over-designed. However, if codes of practice are not used at all then designs may be inconsistent, and in some cases unsafe, particularly if the balance between reliability and the risk of failure has not been adequately considered.

Deterioration and failure processes affecting the performance of Vertical Retaining Walls

In general, the performance of retaining walls will deteriorate with time. There are many reasons for this. Firstly, flood defence walls are exposed to the elements, often in highly aggressive environments. This can lead to a deterioration in performance due to corrosion of structural elements, the loss of passive ground support due to erosion or scour (particularly in storm events), or to an increase in applied loads or groundwater levels. Secondly, environmental situations may have changed over the life of a structure, for example, sea levels, groundwater levels or design wave heights may have increased. Alternatively the owner may need to apply higher loads to the wall (for example, the need for access by heavier vehicles). Finally, the strength of soils around and beneath retaining walls tends to reduce with time due to ‘softening’ This is particularly pronounced for embedded retaining walls which have been associated with excavation or dredging.

A list of the prominent failure modes associated with vertical retaining walls has been compiled as shown in Table 3

Given the above and the ever changing (developing) nature of design codes and practices, there is a frequent need to assess the performance of vertical flood defence walls. This is an onerous and time consuming task which cannot be completed in a short period of time. There is a need therefore for a phased, risk based approach to performance assessments.

Table 3 Prominent failure modes for vertical wall structures

Vertical wall structures
• Overtopping • Undermining by toe scour • Sheet wall collapse by failure of structural members (e.g. tie-rod or anchorage system) • Structural failure due to wash out of fill following joint failure • Structural failure following abrasion or corrosion

Beaches

Description and function
Beaches around the UK typically consist of sand or gravel particles in a range of sizes. The largest particles are usually found on the beach surface, often near the beach crest, while smaller particles are found beneath the surface. The result of this natural sorting of sediments is that typically the surface layers are far more permeable than the underlying finer sediments, which can form a relatively impermeable core. While some beaches have a large proportion of carbonate sand, most beach sediments are of much harder material, often of flint, chert or quartzite. This hardness means that the rate of attrition of individual sand grains or pebbles is low, despite the harsh conditions experienced in the surf zone. The constant wave action, however, results in particles that are generally rounded in shape.

The primary function of a beach is to dissipate wave energy but they also act as an important component of the defences against flooding or erosion of the hinterland. In some areas the upper part provides the only defence against these threats. While the continued presence of a beach has often been assumed as a part of coastal defences, it is increasingly recognised that maintaining adequate beach levels is just as important as the appropriate design and construction of, for example, a seawall.

Accretion and erosion (beach evolution processes)
Beaches by their nature change or adjust their form in response to the action of the sea and the loading imposed by it. As tide and wave energies are always present and changing, beaches are dynamic, evolving continuously in response. The processes of formation or change within dunes, ridges, or roll back of the beach crest are therefore considered not as deterioration, but as part of the evolution process of the beach. These processes are normally cyclic in nature, giving beaches potentially an infinite life expectancy.

However, the state of a beach at a particular time does affect its response to loading and its ability to provide protection in the short term. These changes over time can be monitored. Where a beach forms part of an artificial defence it will almost certainly require monitoring and maintenance to ensure that the required level of protection is sustained.

Deterioration and failure processes affecting the performance of beaches

The performance of a beach is largely dependent on the volume of material and the limits to its plan and profile changes, as particularly influenced by beach management structures associated with it. Where there is a net loss of sediments, then beach recovery is an issue. Where there is clay beneath sand or shingle, it is unlikely that the beach will recover naturally once this layer is exposed. Erosion or changes to beaches are generally gradual (long-term), but significant one-off storm damages do occur.

The failure of a beach is seldom related directly to geotechnical issues associated with the beach itself. In general, failure is a result of a reduction in the volume of the beach through increased longshore and/or cross-shore transport of beach sediment, or a reduction in the supply of sediment onto the frontage. These changes in sediment transport are a result of changes to the wave (and possibly tidal) conditions at the site and can occur for a large number of reasons.

Two areas where geotechnical issues do influence the performance of a beach are in the lower foreshore and nearshore zones. The nature and properties of the sea bed in these areas can contribute to long term changes to the beach profile. The seabed here may be formed from a variety of materials ranging from extremely durable rock through to more easily eroded limestones, chalk and clays. Where durable rock platforms exist there will be very limited erosion and the impacts on the beach profile will be negligible. On softer rocks, the presence of a thin layer of mobile sediment can result in the gradual erosion of the platform through abrasion by constantly moving beach particles. This gradual lowering of the rock platform increases water depths and hence the size of waves that can reach the toe of the beach. These conditions will lead to a loss of beach material and ultimately to failure unless steps are taken to periodically replenish the beach.

At sites where the underlying substrate is clay, erosion can accelerate as the condition of the beach deteriorates. Once the beach has effectively become a thin veneer, the underlying clay is likely to be intermittently exposed during storms and subject to erosion. The loss of this clay beneath the beach profile results in a permanent lowering of the beach and increased exposure to wave attack. This mechanism is commonly referred to as ‘clay down-cutting’ and can result in accelerated losses from the beach prior to failure.

Prominent failure modes of beaches are listed in Table 4.

Table 4 Prominent failure modes for beaches

Beaches **Sand / Shingle Beach** Beach roll-back and erosion are natural cyclic processes Beaches fail when they do not perform their primary function (e.g. resisting overtopping/ tidal flooding/erosion protection), although they may recover with time. Key processes resulting in failure: • Overtopping due to erosion/gulleying/reduced energy dissipation following beach lowering • Failure of control structures
Beach control / wave attenuation structures (ancillary coastal structures) Failure is a failure of the system the structure directly or indirectly protects Key failure modes: • Progressive failure of timber groyne system following deterioration by rotting, abrasion, vandalism, marine borers. • Ship impact

2.2.2 Failure modes of Point Structures

There are many different types of point structures associated with flood and coastal defences. In this instance pumps and gates have been investigated because out of all the types they are probably the most important in most flood defence systems, and also because they pose the most complex problems for fragility curve calculation.

Pumps

Description and function

The primary function of a pump in this context is to remove surplus water from a flood plain area. Their applications in different situations have the same primary function but are determined by different sets of requirements. The reliability of a pump depends on the set of requirements for that particular application. Some pumps are required to operate continuously, whilst others only at certain times. Pumps may be located in sewers or more directly as part of the flood defence system to pump water from, for instance, a canal.

Deterioration and failure processes affecting the performance of Pumps.

The frequency of defects of pumps in sewers is mainly determined by the following factors (Joosten, 2002):

- The composition of the waste water
- The succession of dry and wet periods
- The disposal behaviour of households within the drainage area of the pump

- The type of sewerage system (mixed/separated)
- The technical condition of the system (e.g. subsidence of the sewer leading to sand intrusion, infiltration of groundwater and lost storage)
- The frequency of maintenance and cleaning of the sewerage system and the street surface
- The flow conditions in the sewer
- The type and make of the pump
- The plan of the pump basement
- Air bubbles in the spiral case of the pump or the pressure pipe.

Most of these factors are directly or indirectly related to the amount of debris in the water, apart from these, the main causes of sewer pump failure are considered to be the features of the pump itself and whether air bubbles occur within the pump.

The main recorded failure modes of pumps are as shown in Figure 6.

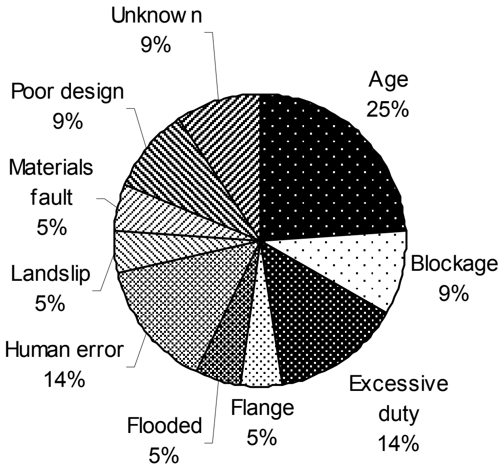


Figure 6 Failure modes of pumps (from Environment Agency 2003b)

Table 5 attributes failures in three main terms which encompasses those above.

Table 5 Prominent failure modes for pumps

Pumps
Mechanical failure • failure of the pump due to blockage or failure of one of the mechanical parts **Electrical failure** • breakage of the cables supplying electricity, interruption of the signal due to a defect in the electrical system **Failure of the overall structure of which the pump forms part** • Overflow / overtopping • Instability of the structure - Piping - Sliding - Overturning - Insufficient strength.

For the failure modes connected to failure of the overall structure, refer to the failure modes of vertical walls in Table 7. For mechanical and electrical failure modes, a failure-on-demand approach must be adopted.

Failure-on-demand is derived in two ways, either;

a) the fraction of time that the pump fails to work (the duration that the pump was defective divided by the total operation time of the pump), or
b) the number of times that the pump fails to work given demand (the number of defects divided by the number of times that there was demand for pump operation).

Furthermore, Korving (2003) points out that the failure modes of sewer pumps differ significantly from pumps applied in polders or in potable water facilities. The composition of wastewater and the discontinuous character of the pumping process account mainly for these differences.

Gates

Description and function
Gates have very diverse functions and vary greatly in appearance and design. A typical example is the difference between a flap gate and a barrier protecting an estuary.

The main function of a *flap gate* is to drain water during low tide (or boundary water level) and to retain water during high tide. The main function of *a barrier*, which protects an estuary, is to retain water during storms.

Deterioration and failure processes affecting the performance of Gates.

Due to the difference in functions and applications of various types of gates, it is not easy to make a list of failure modes applicable to gates in general. An attempt was made to gather the types of failure of gates in the UK based on questionnaires (Environment Agency 2003b). These are shown in Figure 7.

For failure modes connected to failure of the overall structure, see the failure modes of vertical walls in Table 7.

Failure-on-demand and failure rates for a large number of parts in gates are listed in TAW (1997). Failure of one of these parts does not necessarily need to lead to failure of the total structure. An insight into the actual contribution of a single part to a failure event can be gained by a more detailed calculation of the probability of failure of the total structure.

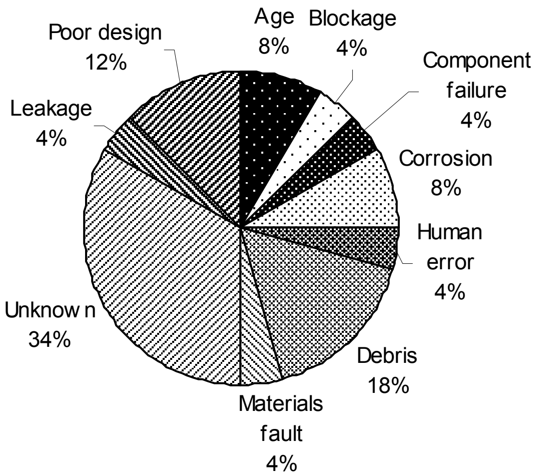


Figure 7 Types of failure for gates (from Environment Agency 2003b)

Table 6 Prominent failure modes for *barrier* type gates

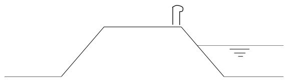
Barrier Gates **Failure of the barrier to close**, due to • Human error • Mechanical failure • Electrical failure **Structural failure of the barrier** • Overflow / overtopping • Piping • Sliding • Overturning **Volume of storage in the estuary is exceeded** - by the flux of water supplied to the system and the maximum river discharge. (i.e. Inputs > than storage + outputs)

As well as pumps, culverts and other point structures, gates should be considered as part of the total system, comprised of coastal and flood defences, in which it is located. For instance, in the case of a flap gate this could be a system of canals and watercourses - which may flood if the gate were to become blocked. In the case of a barrier protecting an estuary, the interaction with the total system of flood defences along the estuary would need to be considered, as a failure of the barrier may not necessarily directly lead to flooding.

Comments with respect to the reliability of other system point structures

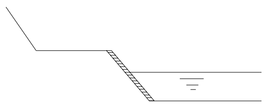
As shown in Defra (2002) a great variety of point structures exist. The importance to consider the fragility of a point structure in the context of the total system of coastal and flood defences seems generally applicable. Environment Agency (2004e) summarises methods to estimate the afflux of bridges and culverts at high flows and the effect of blockages. The probability that water levels locally exceed the banks of a watercourse is a function of a larger system of watercourses, culverts, outlets, etc. The performance of the total system consists of the total capacity of that system, the blockage of one or more culverts, as well as the local afflux.

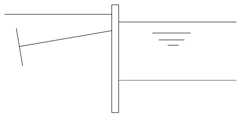
Table 7 Failure modes of linear defences and indicators of failure and deterioration [4]

Flood and coastal defence type	Failure modes	Indicators of Failure	Deterioration	Indicators of Deterioration
Embankment / sloping seawall (defence could include crest wall to embankment, particularly for coastal areas) 	<u>Non-structural failure:</u> • Overtopping • Seepage • Outflanking <u>Structural failure:</u> • Erosion of crest and inside face following overtopping Erosion of outside face • Global slope instability (rotational or translational) • Shallow slope instability • Damage/failure of revetment • Bearing capacity failure • Sliding • Piping • Toe or retaining structure failure • Failure due to presence	<u>Non-structural:</u> • Saturated ground along inner face of defence • Erosion and low points at end of defence <u>Structural</u> • Obvious cutting into slope • Obvious erosion and damage to crest and slope following overtopping • Movement of embankment / wall • Settlement of crest • Obvious damage to, or local movement or abrasion of revetment • Downward movement of embankment/ wall • Lateral displacement of embankment/ wall • Saturated or wet ground along inner face or close to inner toe of defence	• Loss of beach or berm in front of defence • Settlement • Loss of fine material • Long term erosion (e.g. foreshore erosion, gradual slope erosion) • Animal infestation • Cracking/micro-fissuring • Seepage and softening • Vandalism • Crest and slope erosion due to	• Reduction in beach/berm level • Reduction in crest level • Reduction in foreshore level, gradual loss of slope material • Noticeable washout of fine material • Noticeable presence of burrowing animals, holes within embankment • Noticeable cracking (may only be apparent during dry weather) • Soft/saturated areas of defence or ground nearby during high water levels • Obvious vandalism damage to defence • Heavy use by vehicles/ pedestrians/ animals, tyre ruts, vegetation and bank

[4] Failure modes of defences and indicators of failure were undergoing an intense period of research (FRMRC) at the time of writing – the reader is therefore encouraged to seek out the latest equivalent to that provided here.

Flood and coastal defence type	Failure modes	Indicators of Failure	Deterioration	Indicators of Deterioration
	or failure of foreign objects (e.g. cables, culverts, trees, toe dykes and buildings) • Failure/damage to coping/crest wall • Part removal or damage by vandalism	• Erosion at toe, damage or displacement to retaining structure • Noticeable damage at crest of revetment, reduction in crest level • Presence of foreign objects, damage to structure around these • Damage to coping/crest wall • Noticeable damage to structure	heavy trafficking (vehicles, animals, pedestrian) • Deterioration of vegetation • Shallow slips	damage, worn surface and access points • Loss/ increase in extent and quality of vegetation, infestation by invasive plants • Movement of sections of embankment

Flood and coastal defence type	Failure modes	Indicators of Failure	Deterioration	Indicators of Deterioration
Slope protection against erosion 	Non-structural failure: • Outflanking Structural failure: • Toe erosion • Foundation failure • Crest failure • Rotational or wedge slip failure • Failure due to collision by boats / barges • Failure of revetment drainage layer • Failure of slope drainage • Failure due to vandalism • Loss of fines beneath revetment	Non-structural: • Erosion at ends of defence Structural: • Exposure, erosion of toe • Global downward and Movement • Erosion/damage at crest • Rotational movement of slope, horizontal cracking in crest • Noticeable damage to structure • Saturated slope, slips at base of slope • Noticeable damage to revetment • Settlement of revetment	• Loss of watercourse or beach in front of defence • Accumulation of groundwater in cliff above defence • Weathering of revetment • Waves induced by storm or foreign objects causing abrasion or erosion • Movement of individual parts of revetment • Local slips • Animal attack on soft revetments	• Reduction in level in front of defence • Saturated slope or ground at crest of defence • Damage to revetment • Deterioration in general condition • Movement of individual parts of revetment • Movement of structure / slips within cliff • Local holes and tears within revetment

Flood and coastal defence type	Failure modes	Indicators of Failure	Deterioration	Indicators of Deterioration
Vertical wall structures 	<u>Non-structural failure:</u> • Overtopping • Seepage • Outflanking <u>Structural failure:</u> • Toe erosion • Bearing capacity failure • Overturning/loss of overall stability • Collapse • Sliding • Slip failure • Overturning • Failure of structural members (e.g. tie-rod or anchorage system) • Drainage failure • Joint failure leading to wash-out of fill • Direct erosion of retained fill material • Failure/damage to coping / crest wall • Excessive deflection or deformation of wall or	<u>Non-structural:</u> • Low points along crest • Saturated retained ground • Erosion or low points at ends of structure <u>Structural:</u> • Exposure or movement of toe, wearing/removal of toe cover or protection • Downward movement of structure • Leaning of structure or loss of anchorage • Loss of fines or other part of structure, deteriorated joint seals, movement of retaining wall • Lateral movement of structure • Movement of structure, horizontal cracking along crest, toe erosion • Movement of structure, horizontal cracking along crest • Movement of structure, horizontal cracking along	• Loss of beach in front of defence • Corrosion of sheet piles / reinforcement (including ALWC) • Fatigue of steel • Chloride ingress in concrete slabs • Cracking of concrete/masonry • Abrasion • Ground movement • Long term erosion (e.g. foreshore erosion, gradual slope erosion) • Rotting of timber • Wave suction damage to masonry structures • Pointing/joint damage	• Reduction in beach level • Noticeable corrosion, staining of concrete • Distortion of steel piles • Cracks • Surface damage to structure • Movement of retained ground/defence • Reduction in foreshore level, damage to slope • Noticeable deterioration in condition • Unlikely to be apparent • Loss of joint material, erosion around joints, voiding behind structure • Increased extent of vegetation • Seepage through wall (from retained section at low water for retaining walls and from landward

Flood and coastal defence type	Failure modes	Indicators of Failure	Deterioration	Indicators of Deterioration
	foundation	crest • Saturated retained ground • Voiding, settlement of promenade • Loss of retained material • Damage/ reduced level of crest • Movement of structure	deterioration and wash-out of retained fill • Vegetation growth • Leakage through or beneath wall • Cracking and disintegration of concrete caused by sulphate attack or carbonation	face or toe during high water levels for walls with lower land immediately behind) • Cracking of concrete with an irregular pattern, disintegration of concrete surface, corrosion of steel

Flood and coastal defence type		**Failure modes**	**Indicators of Failure**	**Deterioration**	**Indicators of Deterioration**
Beaches	**Sand / Shingle Beach (sand dunes / shingle ridge or beach contained by sea wall)**	<u>Non structural failure:</u> • Overtopping of dune due to erosion/gulleying • Failure of control structures • Insufficient volume of the shingle beach leading to excessive overtopping by long period swell waves or waves during storm conditions • Sand/shingle carry over leading to damage to assets or blocking of road or infrastructure • Restriction of natural beach movement / evolution	<u>Non-structural</u> • Flooding landward of dunes • Damage to control structures, reduction in beach level • Flooding landward of dunes • Reduction in beach level • Presence of sand/shingle landward of dune/ridge • Gullying, unpredictable dune behaviour, particularly where there is an obvious constraint on the system	• Reduction of the volume of sand/shingle in the cross section by erosion due to longshore / cross shore transport • Wind erosion • Lowering/erosion of beach, leading to reduced energy dissipation • Gullying (dune blow-outs) • Long-term climate change (increased storminess, sea level rise)	• Reduction in beach level, increase in sediment supply elsewhere along coastline • Loss in dune crest height, wind-blown sand inland of dunes • Noticeable changes in profile of sections of dunes • Sea level rise, increasing storm frequency and severity

2.3 Summary of dominant failure processes

From the information reported in Section 2.2 we can summarise failure processes into the following:

- Failure due to severe loading (including natural, accidental and vandalism) on defence.
- Failure due to geotechnical instability
- Failure due to gradual deterioration. (This tends to be contributory to the above cases in the majority of failures.)
- Mechanical failure
- Electrical failure
- Human error

Failure processes can be direct or due to a cascade of events[5]. In most cases the occurrence of failure is significantly affected by the already weakened state of the defence. Regarding the use of Failure Modes within performance evaluation, the contribution by deterioration is very important. In fact, most failures of coast protection structures are deterioration led, requiring no extreme event contribution. However the failure occurs, the route can be described in terms of the pathway through the defence as follows:

- Failure creating a pathway through the defence body (e.g. groyne plank failure, joint failure, collapse or blow out of defence).
- Failure creating a pathway over the defence body (e.g. overtopping due to settlement or bearing capacity failure).
- Failure creating a pathway around the defence body (e.g. outflanking of defence).
- Failure creating a pathway under the defence body (e.g. piping and undermining).

The outputs from consultations have shown that generic failure assessments, such as the above, assist in visualising failure of defences at a high level.

2.4 Non-Generic Factors Affecting Probability of Failure

While it is useful to assess future defence behaviour, life expectancy or residual life from generic past performance, it should also be noted that each defence is different and will be affected in different ways by its specific situation.

The following have been identified as important factors affecting the probability of failure and residual life of defences.

- Past performance

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[5] It is important to remember here that 'failure' is defined as *"exceedence of a defined performance threshold/performance indicator. It is also defined as occurring when the challenges to the system (of flood and coastal defence, or any part thereof) exceed its capacity to withstand them".*

- Competent design and construction
- Regular and timely inspection and maintenance
- Materials used for defence construction
- Sub-soil type and foundation
- Environmental condition.

Information about the management of these factors can assist with the assessment of future risk of flooding and expected residual life. Care should be taken with the use of past performance in the prediction of future performance, without understanding the management which has resulted in that past performance, and the future management proposed.

As part of the further development of failure and performance assessment, the ability to incorporate these issues in assessments should be made possible.

3. What are fragility curves?

3.1 Introduction

3.1.1 Outline of the chapter

Section 3.1.2 provides background information on the concept of fragility. A review is made of its place in the overall source – pathway – receptor – consequences model. An introduction is given to the method that has been selected to construct fragility and also an explanation as to what that method entails in terms of the quality of fragility. There is a discussion of the methods utilised to construct fragility for flood defences in different countries and in other industries.

The three main categories in which fragility methods can be grouped are described in Section 3.2. Section 3.3 provides information about how fragility should be considered in different tiers of decision-making and introduces the notions of: '*the fragility curve', 'fragility surface'* and *'multidimensional fragility space'*. Section 3.4 gives examples of the perspectives of different users on which source variables should be used to express fragility condition. Section 3.5 discusses the applicability of the concept of fragility curves in flood risk management. Firstly, the role of the concept of fragility in flood and coastal risk assessments is discussed, and then how fragility represents failure processes and likelihood. Its role in informing decision-making and its link to asset condition assessment is also outlined. Section 3.6 discusses the applicability of fragility to different types of defences. General issues of data needs and availability are highlighted in section 3.8 and requirements for performance and condition assessment in 3.9.

3.1.2 Background to the concept of fragility

The *fragility* of a structure is defined as *'the probability of failure conditional on a specific loading 'L'* (Casciati and Faravelli, 1991) (see Figure 8). Failure is, in this document, defined as failure to achieve stated performance targets. Performance is the degree to which a process succeeds when evaluated against some stated aim or objective. The performance targets of flood and coastal defences should correspond with their primary and secondary functions.

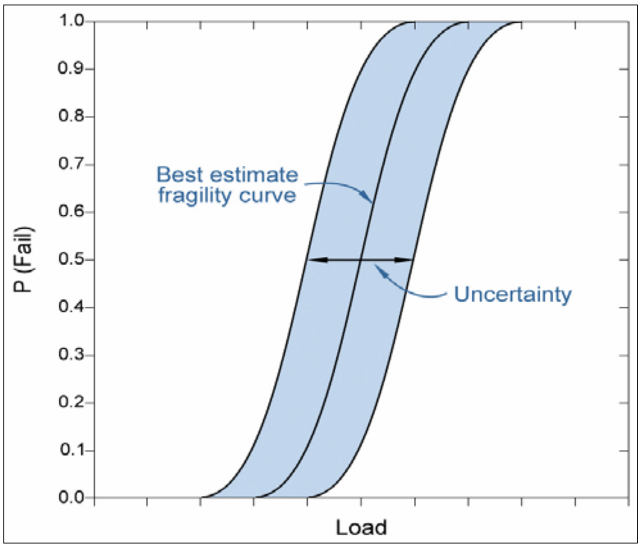

Figure 8 The Generic fragility curve

The concept of fragility was introduced to flood risk assessments to represent the link between the likelihood of defence response (pathway) and different hydraulic loading conditions (source), (Dawson and Hall, 2002, HR Wallingford, 2004b). The place of fragility in the source - pathway – receptor – consequences model is shown in figure 4.

Within this model the consequences, given a number of different possible responses of the pathway, are determined, which in turn are dependent upon different source conditions. The generally applied definition of risk is that it equals the likelihood of an event multiplied by the undesired consequences of that event. In flood risk assessments this amounts to the following:

{Magnitude of flood risk | flooding scenario} =

P(failure of defence | hydraulic loading conditions) x {damage | flooding scenario}

where the hydraulic loading conditions represent the source in the s-p-r-c model.

(Where '|' denotes 'conditional on' or 'given')

The pathway of the hydraulic loading conditions into the floodplain can be either via wave overtopping/overflow, or via failure of a flood defence or an associated structure, which then initiates a breach formation process. The breach formation process of the defence given certain loading conditions results in flooding of an area of the floodplain. The consequences of a flooding scenario are expressed in terms of damage to the receptors in the floodplain.

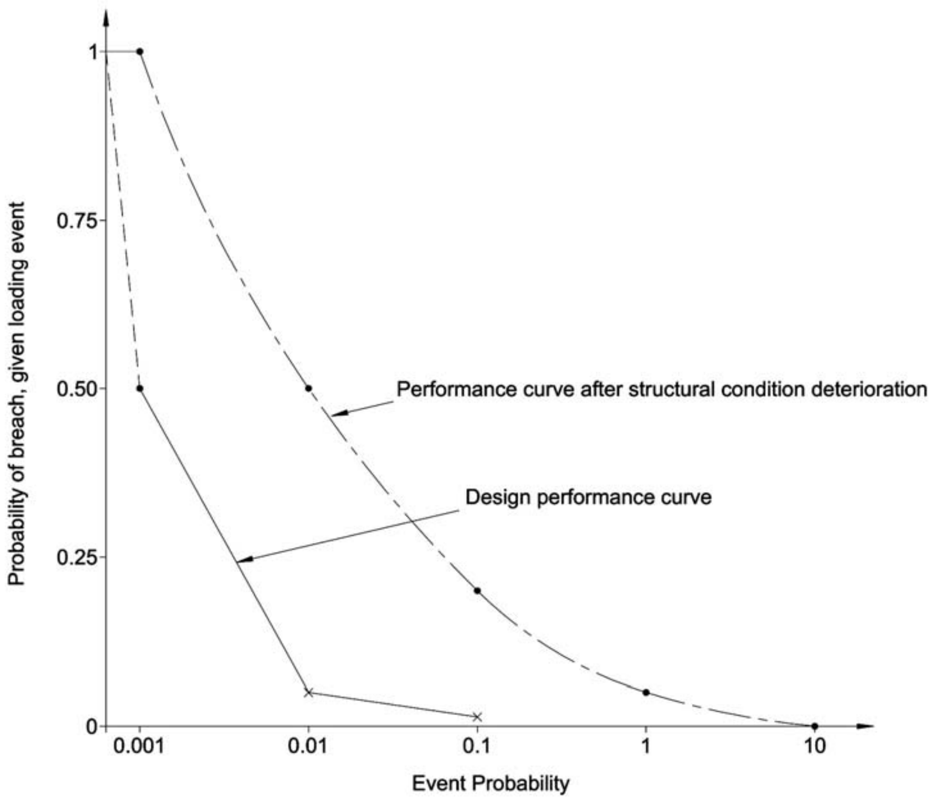

Figure 9 Typical structural breach performance curve

To assess the overall probability of failure of a defence it is necessary first to understand the probability of the range of loading events which will be expressed on the loading axis of the fragility curve. If these are known then the fragility curve can be converted into a performance curve - in which the bottom axis is now a probability of the loading event rather than the value of the load (see Figure 9). The area under the performance curve is then the expected annual failure probability.

3.1.3 Fragility and the representation of uncertainties

Conventionally, the structural performance of a flood or coastal defence is assessed by defining a desired standard of protection (e.g. a maximum acceptable overtopping rate), making a conservative estimate with an appropriate process-based model (e.g. the model to calculate the overtopping rate), and comparing the calculated value with the defined standard. Recently, interest has increased in the importance of considering a range of hydraulic loading conditions and the joint exceedance of sea states, rather than a single extreme combination, supported by software such as JOINSEA.

The lack of knowledge about, and variations in the characteristics of a defence, result in a range of defence responses and associated likelihood. The concept of fragility aims to capture that range of defence responses and likelihood. Figure 10 visualises the difference between the conventional structural performance assessment, and that supported by the concept of fragility.

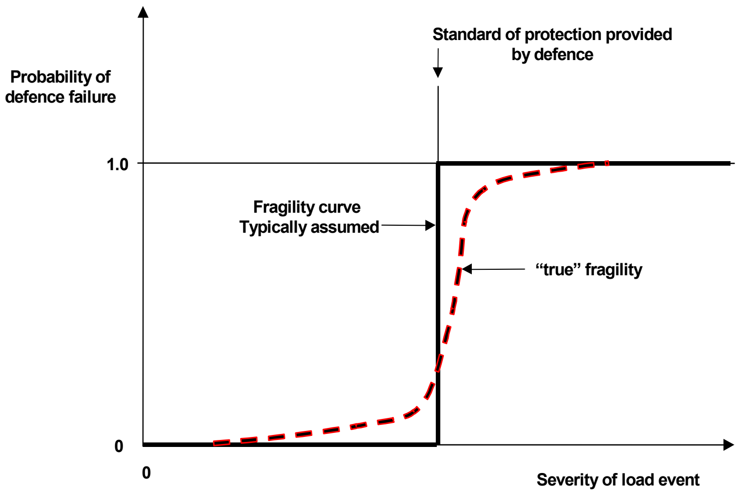

Figure 10 Comparison of fragility approach with conventional approach for reliability

Figure 6.1 in *Environment Agency (2002), Risk, Performance and Uncertainty in Flood and Coastal Defence – A review*, *FD2302*, specifies the generic sources of uncertainty (Natural and Knowledge) inherent within the decision process. How these are represented in the fragility curve is described below.

- Natural variability is subdivided into two main categories:
  - *Temporal variations*
    The hydraulic loading conditions for example are different during each storm, but generally the variations can be represented by a distribution function. If the probability of failure is expressed given a hydraulic loading condition, i.e. as a source variable, the uncertainties are dealt with separately within the overall risk assessment. Temporal variations are inherent in natural processes and it is therefore in general not possible to eliminate these uncertainties.
  - *Spatial variations*
    Ground conditions, for example the volumetric weight of the soil, vary between locations. These spatial uncertainties are represented by a distribution function for that variable. The role of the variable in the failure process determines the importance of these uncertainties to the probability of failure. By measuring the soil properties on an increasing number of locations, the spatial uncertainties can be reduced.

- Knowledge uncertainty is subdivided into four categories:
  - *Statistical inference uncertainty*
    The datasets from which distribution functions for variables are derived, are usually poorly populated for extreme values. The quality of fragility that is based upon extrapolated distribution functions can therefore be compromised. Fragility is in this case improved by increasing the amount of data in the extreme tails of the underlying distribution functions.

- *Statistical model uncertainty*
  A distribution function represents the best fit to a dataset, and therefore does not capture all of the data within the statistical model. The quality of the fragility depends on the quality of the underlying statistical models.
- *Process model uncertainty*
  Process models that quantify failure processes are limited in their representation of reality. Model uncertainties can be quantified and incorporated in fragility. An increasing quality in process based model reduces these uncertainties.
- *Decision uncertainty*
  This is the strength of belief in the decision made and of its robustness. This type of uncertainty is part of the overall decision process informed by fragility and other performance measures and targets.

3.2 The main applications of fragility curves in engineering.

The concept of fragility has been widely used in other industries to characterise structural performance across a range of loadings. These applications can be divided into three main categories:

1. Fragility curves based on empirical data with, as a main requirement, sufficient data of defence failures available for different loading conditions (e.g. earthquake engineering, mechanical engineering). This can be compared to the number of times that identical mechanical parts fail under the same operational conditions divided by the total number of tests.

2. Fragility curves based on expert judgement (e.g. nuclear industry, USACE flood defence). Experts are then asked to quantify their opinion about the probability of failure given a number of specific loading conditions, sufficient on which to base a curve on.

3. Fragility curves based on structural reliability methods employing limit state functions. These are based on the information about failure processes captured in conventional process-based models.

Each one of these groups is addressed in more detail in the following sections.

3.2.1 Fragility curves based on empirical data

Empirical fragility curves can be constructed if there is an extensive amount of data on structural failure under different loading conditions. One engineering discipline that often has sufficient data at its disposal for this is earthquake engineering. The analysis of large seismic events such as the 1994 Northridge earthquake and the 1995 Hyogo-ken Nanbu (Kobe) event enabled empirical fragility curves to be constructed (e.g. Shinozuka *et al*., 2000). Recordings of seismic characteristics (such as the Peak Ground Velocity or the Peak Ground Acceleration) were combined with data on failure of structures to form fragility curves. These curves provide an accurate account of the response of structures to certain seismic conditions. However, they are only relevant to the location for which they are derived and they cannot be held to apply to different types of structures.

Another example of an industry which has enough data is mechanical engineering (examples in Meeker and Escobar, 1998), for example in the analysis of material fatigue. In this case the data available is the result of repeated tests on identical parts in a controlled environment. However, again the results are restricted to the same type of components and operational conditions for which the tests have been conducted or designed.

3.2.2 Expert judgement

Many engineering applications are not suitable for empirical data analysis, e.g. due to time constraints or the difficulty of simulating operational environments. Here, use is often made of expert judgement. One example is a method that is frequently employed in the nuclear industry where a fragility curve is based upon a lognormal distribution and a 'HCLPF'. This acronym stands for *High Confidence Low Probability of Failure* which represents the value of the loading for which there is a 5% or less probability of failure with 95% confidence. The HCLPF value is based on expert judgement or, if available, failure data. Two examples can be found in Ellingwood, 1998, and Commandeur and Curry, 2004.

In the flood defence industry in the USA a concept similar to the fragility curve has been applied albeit under a different name (see USACE, 1996). The failure-probability function is used to express the probability of exceedance of the capacity of the flood defences given different water levels. The function is derived by establishing two critical water levels. One is the level for which the embankment is not very likely to fail - the 'Probable Non-failure Point' with a 15% probability of failure. The other level is the 'Probable Failure Point' for which the embankment has an 85% likelihood of failure. Between these two points on the curve, straight lines are drawn.

3.2.3 Structural reliability approach

Structural reliability methods based on physical process based models can be used to construct fragility curves where there is a lack of available data or where it is desirable to expand the analysis beyond expert judgement (see Thoft-Christensen, 1982). Structural reliability theory calculates the probability of failure of structures by analysing the main modes of failure and representing these failure mechanisms with limit state functions. A limit state function in its general form is expressed by $Z = R - S$; in which R represents the strength of a component or subsystem and S stands for the loading imposed upon it. If the loading S, exceeds the strength R, then the component or subsystem fails ($Z<0$).

Probabilistic calculation methods are available to calculate the probability of failure based on the limit state function. A fragility curve can be constructed by calculating the probability of failure given a range of deterministic loading conditions. Physical process based models, ranging from simple relations to complex finite element models can be used to represent the strength and the loading of the structure.

In the Netherlands, a structural reliability approach for earth embankments is well developed and although still experimental, will soon be applied on a large scale. Similarly in Germany the structural reliability approach for flood defences is increasingly receiving attention.

An interesting alternative to the classical probabilistic theory of dealing with uncertainties in strength and loading models is offered by the theory of imprecise probabilities. The uncertainties in the strength of flood or coastal defences are often dominated by a lack of knowledge. The variation in the parameters in the strength model are then chosen to be represented by the theory of imprecise probabilities in the form of interval bounds on an unknown value, or, more generally, by constructing a 'fuzzy' set over an unknown value. Such a fuzzy set specifies the degree of membership of certain parameter values to the set under consideration. The attention that the application of this methodology to flood and coastal defences has been receiving is of a recent nature, but an example of its application can be found in Dawson and Hall, 2002.

3.2.4 Recommended application in the flood and coastal defence industry

The structural reliability approach as described in section 3.2.3 is recommended in coastal and flood defence reliability analysis. Sufficient data about failures of a particular defence given a loading condition, as in 3.2.1, is not available. Expert judgement alone, discussed in section 3.2.2, ignores the existing knowledge about physical failure processes. Structural reliability methods simulate defence failures based on the best available knowledge about the physical processes, but also allow expert judgement for filling in the gaps. These processes are represented by models that are routinely applied in practice to assess the performance of structures. The quality of the fragility results therefore, hinges on the quality of:

- the underpinning process-based models;
- the statistical representation of those models and data;
- the data available;
- the accuracy of the chosen calculation methods.

Although this structural reliability method is also subject to judgement-based influences, the underlying process-based or probabilistic models make the results more accessible to external scrutiny.

3.3 Fragility in the different tiers of risk assessment

The overall risk assessment methodology is consistent within all levels of flood risk management (see Figure 5), but the quality of fragility representations improve with an increasing level of detail. As mentioned in section 3.2.4, the quality of fragility hinges on: the quality of the underpinning process-based models, the representation of the uncertainties in those models and data, the availability of the data, and the accuracy of the chosen calculation methods. Figure 11 shows how the increasing level of detail affects the uncertainty bands on the fragility curves.

The tiered structure implies different levels of risk assessments ranging from broad-scale to local scale assessments, or ranging from the feasibility to detailed design stages. Broad-scale risk assessments of coastal defences will often require delivery of results in the short term with limited investment resources. This requirement leads to the use of general data that is easily acquired, and to the simplification of the process-based models applied to represent the failure processes underpinning fragility. Such a simplification reduces the data requirements and the complexity of the calculations. As illustrated by Dekker (1996), and Dekker and Scarf (1998), other industries are coping with a similar situation. They identify the paradox that the amount of money involved is highest and the importance of the decision is greatest at the (broad-scale / national) level where both the amount and accuracy of the information is lowest.

The required shape of fragility can vary according to the different levels of risk assessment. When fragility is determined given one source variable representing a loading condition, the results can be expressed in the form of a *fragility curve*, as in Figure 8. When fragility is calculated given two source variables, the results are expressed as a *fragility surface*, and the plot is three-dimensional. Fragility can also be calculated given more than two source variables: *multidimensional fragility space*. It then starts to become harder to visualise fragility and representation reverts to the form of a table, or extends to several plots. Another option is to reduce multidimensionality of, for example, three source variables to one, through a response function.

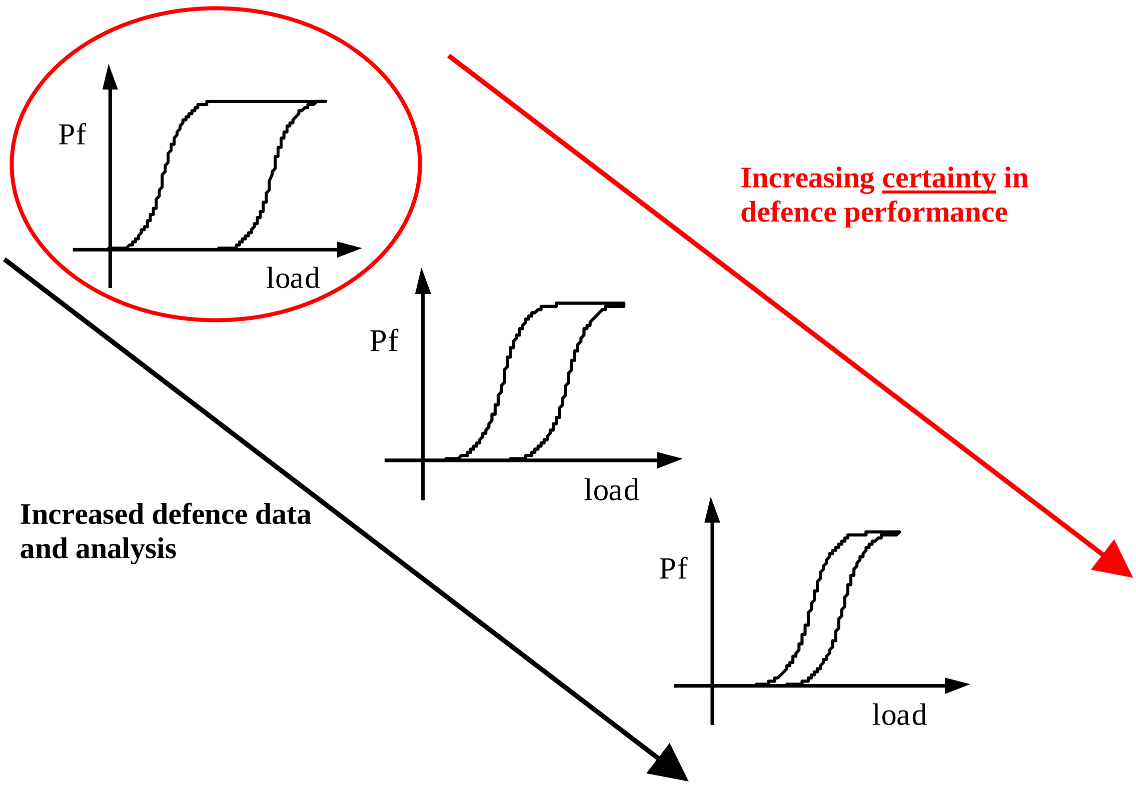

Figure 11 Increasing detail of analysis delivers an increasingly reliable understanding of defence fragility (from HR Wallingford (2004a).

(The generic fragility which is provided in Volume 2 (TR2) is representative of the encircled level)

3.4 Different user perspectives on the shape of fragility

As mentioned in section 3.3 the shape of fragility can vary according to the different levels of risk assessment. This section aims to discuss some of the different perspectives regarding the desired shape of fragility. Different users may require a different shape of fragility to enhance understanding of the information presented. There are potentially many user groups but the main ones identified are:

- Numerical modellers of a flood and coastal risk assessment require fragility that is quantified in such a way that enables them to run their model efficiently. Fragility is expressed conditional on the source variables. The main requirements are the form in which the source variable is available and how the total framework of the risk assessment model is set up. These requirements purely make efficient 'number crunching' possible. Two examples are:
  - for National Flood Risk Assessments the hydraulic loading for coastal flood defences is provided in the form of overtopping discharges and return periods. The framework of the software code is set up accordingly. A requirement for fragility is then to express the probability of failure given an overtopping discharge

- for intermediate level Flood Risk Assessments (at a regional/strategic level) fragility is expressed given water levels and wave heights. Joint return periods are associated with water levels and wave heights. This smaller geographic scale of the risk assessment enables computationally more intensive methods.

- Operational flood and coastal defence managers require a fragility shape that allows straightforward interpretation. Ideally, fragility should allow them to make a judgement about the state of a structure 'in the blink of an eye'. For instance, the probability of failure given overtopping discharge values allows a direct comparison with familiar measures, for example, indicative critical overtopping discharge values presented in the Rock Manual. Such comparisons allow quick judgements to be made on whether the state of the structure has deteriorated or has remained more or less stable. If a manager wants to look at how a particular defence might perform under different loading conditions then the fragility curves need to be worked into a more appropriate form. Only expressing the curves against water level does not show how the water level and wave conditions are correlated locally. In the overall risk assessment this is addressed in the total computation, but is not reflected directly in the fragility. For a more appropriate impression the local distribution function of the wave height and peak wave period should be integrated within the fragility – then the 'real' performance of the structure against water level is represented.

  The structure of process based models sometimes limits the potential to form simplified fragility representations to aid interpretation or faster 'number crunching'. In such cases fragility is represented against the source variables in its process-based models relating to the consequences of flooding.

- Another interesting group are evacuation or emergency managers. They require the expression of the probability of failure given a source variable that they can quickly assess, rather than judge against, for instance, familiar performance measures. It is easier for example to quickly estimate a local water level than an incident wave overtopping discharge.

- Designers may wish to use fragility methods or tools to help specify designs for new structures or define remedial actions and repairs. It will be especially useful where strategies and policies require certain standards of performance and reliability, and a reduction in risk from structural designs and modifications, as well as standards of protection.

3.5 The applicability of fragility curves in flood and coastal risk management

Since its introduction in risk assessments, the concept of fragility has been successfully applied in a number of case studies and in national flood risk assessment in the UK (Defra, 2002, Hall *et al*, 2005). In recognition of the useful role of the concept of fragility in these cases, it was decided to investigate its applicability to more detailed risk assessments of coastal and flood defences. In this discussion attention is given to the two following issues:

1. The role of the concept of fragility in flood and coastal risk assessments - this part discusses the types of risk that the concept of fragility represents and the extent to which it can serve to provide information about the reliability of the defences.

2. For which coastal defence types and failure modes associated with them, it is possible, in a practical sense, to construct fragility curves.

Risk assessments of flood and coastal defence systems aim to capture the likelihood and consequences associated with failure processes. For successful implementation in practice, there is a need to return the results of the risk assessment in the form of informative indicators. In this section some aspects with respect to the role of the concept of fragility in flood and coastal risk assessments are discussed. The discussion is structured around the following questions:

- How does fragility represent the failure processes defences?
- How does fragility represent the likelihood in the *risk = likelihood x consequences* relationship?
- How does fragility inform decision-making?
- How does fragility link into condition assessments?

3.5.1 How does fragility represent the failure processes of defences?

Fragility represents failure processes using limit state functions incorporating conventional physical process-based models. A useful by-product is that the calculation for each failure mode points out how the different physical characteristics of the defence contribute to failure (see figure 12). It is also possible to combine the fragility of different failure processes. Such combined fragility provides insight into the most prominent failure mode. The concept of fragility can therefore be used to summarise the physical characteristics and response of flood or coastal defences. As discussed in section 3.2.4, the quality of the results depends on; the quality of the underlying process-based models, the representation of the uncertainties in the data and in those models, the data availability, and the accuracy of the chosen calculation methods.

In some cases the failure process requires additional analysis - especially when time-dependency comes into play. Examples are:

- When the failure process depends on the history of loading.
  The sequence of loading determines how the failure process develops - such as the influence of the sequence of rainfall events on the hydrological state of a cliff. The rate of erosion depends on the hydrological state of the cliff.

- When, due to a deterioration process the failure of a defence takes place between storms, there is a discrepancy between the loading conditions during structural failure, and the consequences caused by storm conditions (implying other hydraulic loading conditions).
  Additionally, damage can then occur simultaneously with failure of the defence. One can think of a sheet pile wall which retains ground on which houses are built. If the sheet pile wall collapses, due to accelerated low water corrosion between storms, the houses will be damaged. Without intervention the next storm may lead to erosion or flooding.

3.5.2 How does fragility represent likelihood in flood and coastal risk assessments?

Risk assessments of coastal defence systems require appropriate representations of likelihood and consequences of the failure processes. The concept of fragility as a function of hydraulic source variables is applicable to coastal and flood risk where the failure of the defence and the consequences of failure are both directly related to the hydraulic loading conditions. As mentioned above, care should be taken where there is a discrepancy between the moment of occurrence of the failure process, and the consequences. Extra analysis is then required to combine the correct likelihood with the consequences. An example is the failure of coastal protection against erosion during a storm. The fragility of a revetment during a storm must be combined with the probability of different erosion rate scenarios and the associated damage following the revetment failure.

Another issue is when the risk assessment serves to underpin decision-making covering a wider spectrum of problems than just flooding, for instance, maintenance and inspection. A risk definition solely based on flooding might turn out to be too narrow. A flood or coastal defence can for example, also fail to perform other functions. Analysing the primary and secondary functions of a flood or coastal defence helps to identify whether all types of consequences are taken into account. It may be necessary to extend the concept of fragility, or to use another solution to represent the likelihood associated with other consequences and types of failure. Two contrasting examples are:

1. Flood defence
   The most obvious example is a flood defence with a primary function of water retention. When it fails for instance, due to overtopping under storm conditions, the consequence is that the hinterland floods. The fragility curve expresses the probability of failure given different hydraulic loading conditions. It represents failure of the primary function and the probabilities of flood defence failure given the hydraulic loading conditions, appropriately connecting the source with the consequences.

2. Coastal protection
   The main function of coastal protection is to prevent loss of land due to coastal erosion. Failure of coastal protection against erosion depends on the hydraulic loading conditions imposed upon it, for instance, in the form of water level and wave conditions, or in the form of accumulated hydrological

pressures behind a revetment. If coastal protection is not in place, erosion of the coast can progress over time leading to loss of land and possibly of assets located on that land. The consequences therefore depend upon the coastal erosion rate following failure of the protection. If a fragility curve is constructed to capture the probability of failure of the revetment given hydraulic loading conditions, then this curve does not connect the source with the consequences. Here then, additional analysis is required of the probabilities of the erosion rate and the consequential damage scenarios.

3.5.3 How does fragility inform decision-making?

Fragility contains information about the structural reliability associated with different failure processes of a defence. Structural reliability is thus mapped onto one measure allowing comparisons to be made not only between failure processes but also between different defence sections. However, in some cases, the information contained within fragility must be made more accessible for decision-makers. Reasons for this are:

- It is relatively hard to translate the interpretation of a fragility surface or of multidimensional fragility into concrete actions. Working fragility into the total probability of failure, or the contribution of the defence to the total risk are examples of how to make the information in fragility more accessible to decision-makers. The requirements for accessibility by decision-makers depend, for instance, on the type and tier of the decision it aims to inform, the background of the decision-maker, etc.

- Different locations along the defence system are hard to compare based solely on fragility due to the separation of the strength and loading of a defence. If two coastal flood defences have the same probability of failure given different hydraulic loading conditions, but one of the two is subject to heavier wave attack, then the one under heavier wave attack performs less well and hence deserves more attention. Again, working fragility into a total probability of failure or contribution to risk will make the information more accessible.

- ‘Snap shot’ assessments of reliability might not adequately inform the decision-maker. In some cases more options might have to be compared in a time-dependent cost benefit analysis.

3.5.4 How does fragility link into condition assessments?

Another important part of flood and coastal risk assessment is the condition assessment. Decisions about maintenance, repair and improvement options are made based on the outcome of the performance assessment. The performance assessment is informed by the condition indicators coming from the inspections, be they visual inspections or more detailed measurements. How these links are made is being studied as part of the ‘PAMS’ (Performance-based Asset Management System) project (see section 1.2).

Fragility characterises structural performance based on condition indicators from inspections and informs decision-making. As mentioned in section 3.5.1, fragility provides information about the sensitivity of the probability of failure to the different variables in the physical processes at work. That information points out which variables should be prioritised in inspection, improvement and repair decisions. In the mean time, inspections should be as closely related to those variables as possible. Achieving close relations ensures the quality of the information fed into the performance assessment. It is especially challenging in the case of superficial visual inspections, to find indicators that are directly related.

In addition to the sensitivity of fragility to the variables in the process-based models, it also allows the deterioration of the asset to be taken into account. Inspection or monitoring, reviews the process of deterioration, which should then trigger other actions (such as maintenance, repair or specialist investigation and assessment) to deliver performance expectations over time. In order to accomplish this, first, a realistic defence fragility curve must be created that reflects the design performance envelope for the asset that links the probability of an event to the consequence of it. The fragility curve should then be ‘managed’ within the envelope to maintain the performance expected at the design stage, over the life of the asset (in the most cost effective way).

Thus – fragility curves approaching the bounds of their ‘envelope’ should trigger actions to identify and rectify the cause of the shift which might include new works or changes to the management regime. If the method fails to trigger interventions then there will be an increased risk of an unexpected consequence for the magnitude of an event experienced.

It should be noted that the definition used for inward and outward faces are based on existing asset inspection definitions, namely the inward face is that facing the flooding source and the outward face is that facing landward.

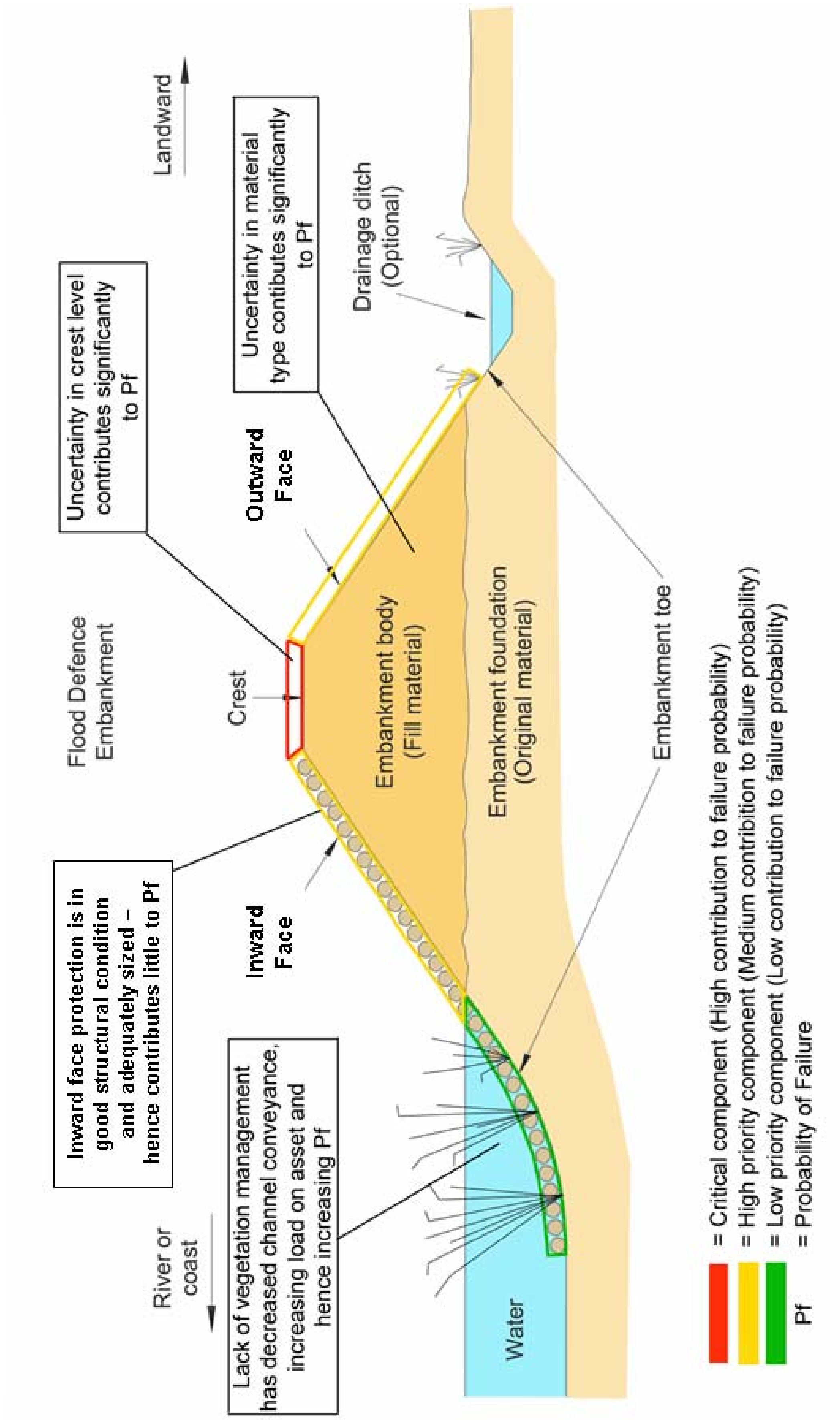

Figure 12 Example of the effect of defence components on probability of failure and thereby fragility

3.6 Applicability of fragility to different defence types

The applicability of the concept of fragility to different defence types was evaluated taking the following main issues into account:

- The ability to represent the physical processes in fragility in different tiers of risk assessment varies for the failure modes and defence types. Problems that are encountered are:
  - Appropriate process-based models and straightforward ways to incorporate them in a tiered risk assessment structure are not (yet) available for all failure modes. Specifically, geotechnical failure modes pose challenges. For conventional deterministic reliability analysis, finite element methods and often simplifying equations are available, but questions that remain include: how to incorporate those finite element analyses into detailed risk assessments, and are those simplifying equations sufficiently representative of the underlying processes.
  - Although failure of vertical wall structures and coastal protection can be the result of a storm, their failure might not necessarily lead to flooding. Instead, their failure is partly related to direct damage to assets and partly to a complex erosion process over time that has a history of load dependency. In addition, failure of these structure types often occurs between storms as a result of a deterioration process. For example, when the dominant loading of the structure is not hydraulically load-dependent, such as in the case of ground retaining structures.
  - The necessity to consider point structures in general in the context of the total system of watercourses or flood and coastal defences, in order to form an impression of their relative importance. Once an individual point structure turns out to be important, its individual fragility serves to underpin decision-making about how best to improve it. This point is explained below in more detail.

- The availability of physical process-based models to underpin probabilistic calculations. The quality of the available process-based models for the main failure modes of defence types varies. Some physical processes have received much attention in the past resulting in well developed process-based models, e.g. overtopping models. Other physical processes are currently poorly understood, e.g. erosion / scouring or fissuring and cracking. The quality of fragility will improve as the knowledge and understanding of these physical processes increases.

The reasons to consider failure of pumps and gates or other component structures in a system-based context rather than as a stand-alone failure are:

- Pumps are part of a bigger system usually of canals and watercourses which can be described in terms of system capacity (storage volume + pump capacity, etc.) and loading volume (rainfall). The fragility method can be used to describe failure of this system.

- Gates have more diverse functions and more variation in form (e.g. flap gate versus barrier). Even between two failure modes the loading conditions governing a flooding event can be different (e.g. in the case of a barrier). However, if gates are correctly separated according to function and type, the fragility method can be used to describe the probability of failure in these different categories.

- System effects should also be taken into account for other point structures such as culverts, or constricted flow due to a bridge. Local afflux and the probability that the water level will exceed the bank of the watercourse could be included.

3.7 Time-dependent reliability

The concept of fragility provides a snapshot of the probability of failure in time. The description of time-dependent reliability requires a series of snapshots in time, and therefore a series of fragility curves in time.

Limitations of applicability of the concept of fragility to capture time-dependent reliability are related to:

- Whether the failure mode which is affected by deterioration can be captured by a fragility curve;

- Whether physical process based and statistical models are available to describe the deterioration process.

It seems that deterioration processes have not really been an integral part of conventional deterministic reliability analysis. Process-based models for deterioration processes are less developed and organised than those describing reliability as a snapshot in time. Deterioration processes can be incorporated in fragility by analysing which failure modes they affect. Deterioration can trigger seemingly irrelevant failure modes and is therefore sometimes confused with the failure mode. Examples of the challenges that time-dependency introduces are:

- The representation in fragility of failure processes that are historically load dependent. Processes that have already been mentioned are: (coastal) erosion and scouring, cracking and fissuring

- Process-based or statistical models that take dominant factors into account in the deterioration of structures, such as third party use, animal burrowing, and tree rooting, are relatively poorly developed. The statistical occurrence of the ‘loading’ by an animal population, third party use or a tree blowing over is one aspect of the problem. Another aspect is the physical quantification of the damage to the structure, and which failure modes that damage affects.

- In some cases the sensitivity of fragility to the variables in the process-based model does not fully cover the importance of that variable. Especially when that variable is representative of a defence element that fulfils more than one important function. In that case, whole life cycle costing can offer a solution.

An example is vegetation, which, besides its protective function during a storm also offers daily protection against third party use and rainfall.

3.8 Data needs and availability

The Fragility Method requires a range of data (as shown in Appendix 7), and an assessment of the adequacy, reliability and accessibility of such needs should be made. Additional data collection can then be undertaken if necessary. It may be necessary to commission new topographic or geotechnical surveys for instance to obtain the required data. To provide an impression of the type of data required, a list of data requirements is given in Appendix 7 for the calculation of generic fragility. .

Some general issues related to data requirements are listed below:

- Flood Risk Assessments may promote a prioritisation of data requirements and associated surveys based on urgency.
- The availability of inspection or survey resources may limit the amount, accuracy and reliability of data available for this methodology.
- A critique of the data used should be undertaken so that a judgement as to the ‘integrity’ of the outputs can be made when assessing fragility results.
- The NFCDD currently contains minimal data with which to construct fragility curves, and at the detailed defence level, extra data from other sources will invariably be required.
- Significant paper data often exists on existing assets including for example:
  - Design drawings
  - As built drawings
  - Geotechnical data from boreholes and trial pits
  - Repeat inspections (for instance showing deterioration in crest levels and structural integrity)
- Digital data may also exist in the form of Lidar (airborne topographical survey) data
- For pumps and gates, a limited number of pilot studies and performance targeted data collections could provide additional insights into the availability of local (failure) data sources. From consultations with practitioners it has emerged that local internal drainage boards might be able to facilitate such pilots. These pilot studies could provide insights into how to approach pumps and gates in terms of a probabilistic approach. Approaches implemented abroad should also be considered.
- Structural data may often be sourced from ‘as built’ drawings which may be very old. Consideration and appropriate remediation of the data should be made to account for structural deterioration and degradation during the time elapsed.

3.9 Information requirements for Performance and Condition Assessment

The quality of fragility outputs, aside from the process models on which they are based, is largely down to the information on the defences that is available. Any data gathering method should thus ideally be tailored to this end or at least include the opportunity to collect the necessary information for application in fragility calculation.

The performance assessment of flood and coastal defences addresses a range of different aspects. The extent to which flood and coastal defences provide protection against flooding or erosion is one aspect. *Reliability* is another, and is a function of physical process based models of strength and of loading of the defence.

Maintenance optimisation models tend to have two important dimensions:

1. the tiered structure of the system, and
2. the structure in the time domain.

No ‘structure’ has yet been defined for the time domain: e.g. risk assessment intervals, inspection intervals, maintenance planning (The latter two are to be determined in a risk-based manner as part of the development of the Performance-based Asset Management System (PAMS)).

Decision-making in this system is informed by means of indicators. The following requirements for indicators have been drawn from applications in other industries:

- A clear difference has to be made between condition indicators and performance indicators. Condition indicators are the result of observations made during inspections – which must be objective and repeatable. Performance indicators may be derived after applying calculations with a model (using condition indicators).

- The indicators should be tiered and range from simple (for small-scale decision-making) to complex (as part of complex risk assessments in large-scale performance assessments).

- Throughout the tiers, indicators should be risk-based in some way and based upon the same models to determine the risk. For instance, assessments applied to flood defences in the US use a condition index where different condition indicators are used to derive a performance indicator. One main drawback of this method is that the results from different flood defence sections, used to derive the condition index, are not comparable. Using indicators that are risk-based could solve this drawback.

- It should be clearly defined which types of decisions and actions the tiered indicators are meant to inform. The information provided by the indicators must support the decision to be taken.

- Lower level indicators should be suitable to update the more complex risk assessment whilst supporting small-scale decision-making.

An important conclusion is that the approach to reliability and risk should be based on the same physical processes - whatever the tiered level of analysis may be.

4. Methodology to build a fragility curve

4.1 Preparation and data requirements

When analysing a system of coastal defences with the intention of determining system reliability, the activities are generally:

- to translate physical reality into a (probabilistic) model,
- to express this model into data, and
- to generate fragility with calculations based on this data.

The steps involved in preparing the calculation of fragility are shown in the flow diagram in Figure 13 (based on that shown in Buijs *et al*. (2003)). These are the same for risk assessments of increasing detail.

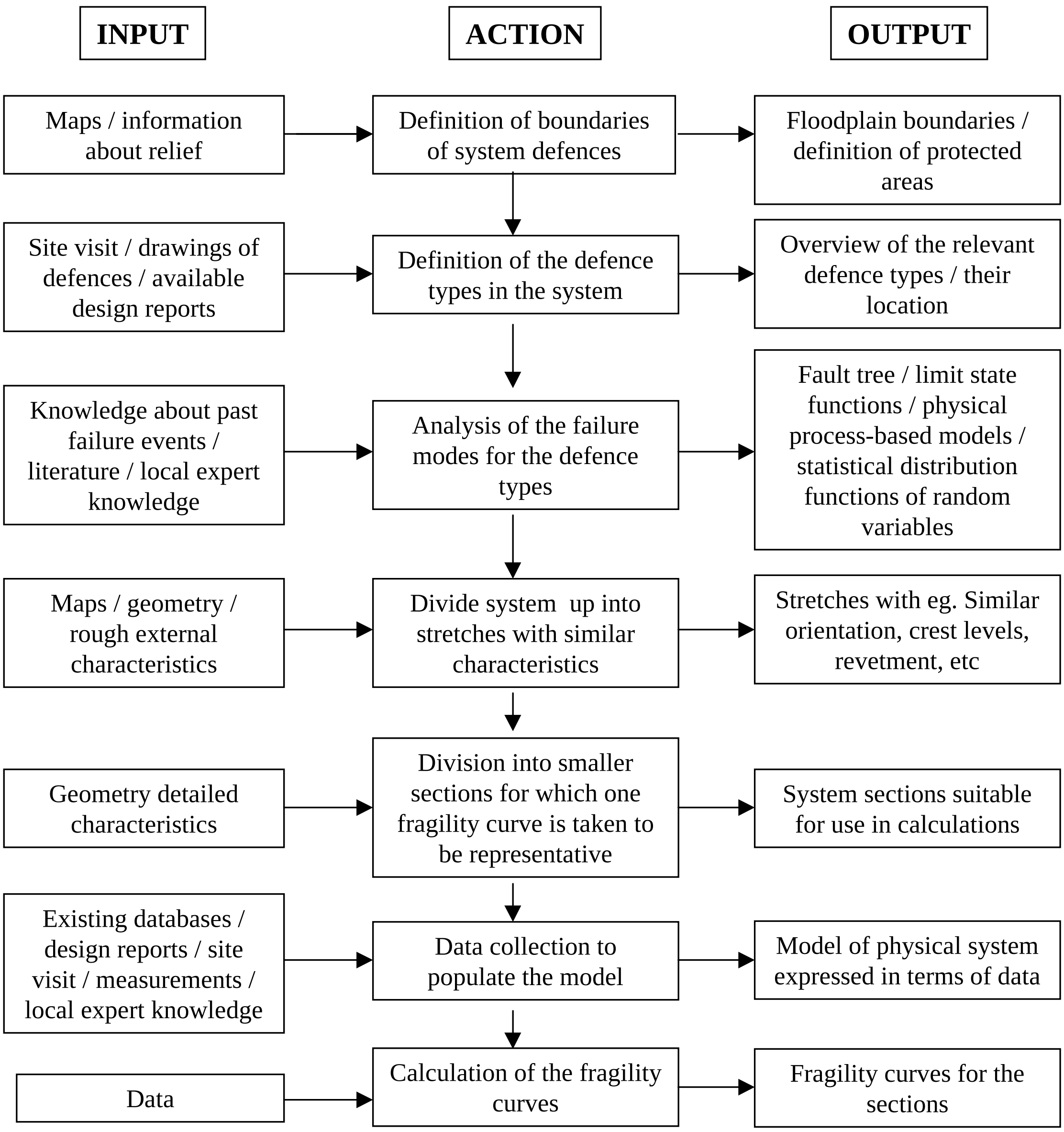

Figure 13 Steps in the production of fragility curves

The physical reality does not change for the same system in the different levels of risk assessments, but the data availability and decision needs do vary. This may inevitably result in the choice to use a simpler representation of failure processes, or in the decision to work with rough data (as opposed to detailed).

4.2 Detailed steps to take in constructing generic fragility for a dominant failure mode

The methods and assumptions on which fragility is based are partly dependent on the amount of information available at the desired level of decision-making. It is reiterated that fragility is a function of physical process models of strength and loading of the defence, and that the approach of reliability should be based on those models whatever the tiered level of analysis may be. Therefore, for each defence type, the process-based models should be chosen in harmony with the available information corresponding with the required detail of the risk assessment. The method we have chosen and described below was used to calculate the fragility curves shown in Appendix 4, however, there may be variations to this.

In the absence of detailed information, fragility curves for a given defence structure and failure mode can still be constructed using expert judgement. However, wherever sufficient information is available then more evidence based fragility curves can and should be developed.

The following stepwise approach can be used to build fragility curves for a given failure mode without having to resort to a full reliability analysis[6]. The results are therefore recommended for use in broad scale risk assessments. For decision-making on operational issues more detailed reliability analyses are recommended.

1. <u>Identify the main structure types in the flood and coastal defence system under consideration.</u> For broad scale flood and coastal risk assessments that amounts to a generic classification of all the defence types in the total scope. At the regional or defence scheme level, it amounts to the structure types in that region or for example, a system of defences protecting one floodplain.

2. <u>Identify the main performance targets, or functions, of the defence types resulting from step 1.</u> This allows a definition of failure and the identification of the source variable(s) on which the magnitude of the consequences is dependent.

3. <u>Make a comprehensive overview of the failure modes and their mutual relations of each relevant defence structure.</u> These failure modes can be established in a combination of desk studies and elicitation from

[6] This method is considered to be good practice but there may be variations as to how it can be done. This is the method used to generate the fragility curves in the Appendices.

practitioners or experts[7]. Express the failure modes in a fault tree, showing for each failure mode the sequence of events that eventually leads to failure. The relations are qualitative representations in terms of a logical OR-gate, AND-gate, etc. Detailed definitions can be found in the glossary under *logical gates* and *fault tree*. See e.g. the fault trees produced for the main defence types in Appendix 3 of this report.

4. Identify the *single failure mode* that is considered to be the most likely to occur and thus to be representative of failure of the defence[8].
   Note: If s*election of just one mode is not possible*, then it will be necessary to consider more than one mode and identify the loading ranges where each failure mode is most dominant. It may be necessary to analyse across the full range of potential loadings to identify their cross-over points.

5. a.) Establish information availability corresponding with the tier of the risk assessment
   b.) Identify an appropriate "model" to represent the failure mode. In many cases this model will be some kind of equation, but in other cases (e.g. slip failure) this will not be possible. The important thing is to have clear definitions for "failure" conditions; in most cases this will be the Ultimate Limit State (ULS) but sometimes the Serviceability Limit State (SLS) may be applicable. Limitations as to the information available will prompt the choice for more simplified representations.
   c.) Identify the key *source variable* of interest for the structure – as it relates to the eventual consequences and the type of user, see section 3.3 for examples of users and their desired fragility shape. This can be any source variable of interest.

6. Recast the equation or model in limit state form:

   Z (reliability) = R (strength) – S (loading; not source variable dependent) – S(loading; relevant source variables)

   where R will represent the gathering together of all terms or variables which relate to the strength of the structure and S will represent the gathering together of all terms or variables which relate to the magnitude of the loading.

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[7] The examination of failure modes requires detailed and expert analysis, however the fault trees provided in Appendix 3 were based on established and expert knowledge collated during this study, and form the basis of more specific, detailed fragility analyses.
[8] The allocation of a singular failure mode is far from ideal and can lead to not insignificant assumptions. Further work to look at assessment and testing of methodologies for combining multiple failure methods is vital to reducing uncertainty and the achieving more robust outputs.

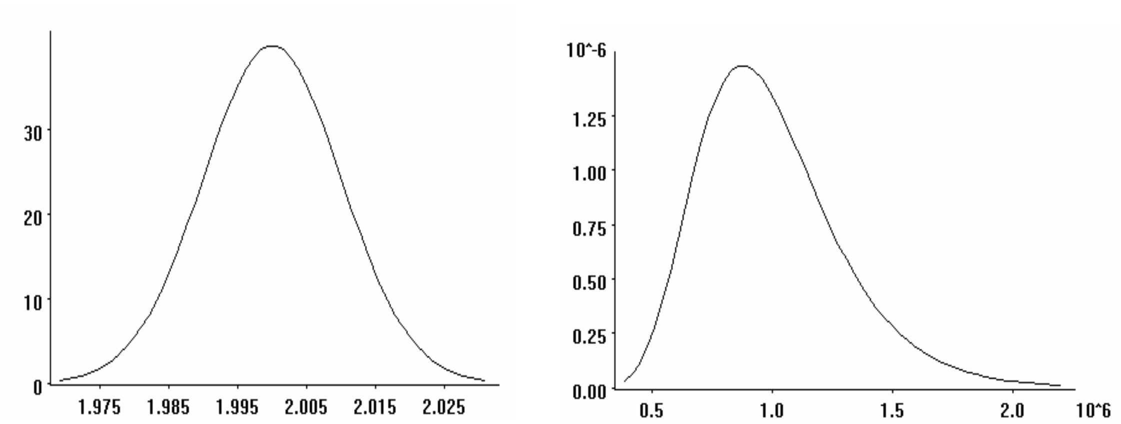


Figure 14 Normal and log normal distributions

7. Define the statistical properties of the variables and the engineering models, resulting in distribution functions, mean values and standard deviations. For all the variables or terms relating to the strength and loading that are not a function of the relevant source variables, identify the following:
   (a) The form of variability expected for the variable. In most cases, this will be one of the following statistical distribution functions (see Figure 14):
   - Deterministic
   - Normal distribution
   - Log normal distribution

   (b) The mean value for the variables
   (c) The standard deviation for the parameter[9].

8. Derive the fragility curve using Monte Carlo analysis.
   To understand how this is achieved note first that each point on the fragility curve expresses the probability of failure for that loading condition. Failure arises in a particular case when the combinations of parameter values in the limit state function Z, gives a value for Z which is less than or equal to zero. The probability of failure for that loading is then the number of times Z is less than or equal to zero divided by the total number of possible events

[9] A crude approach to deriving a estimate of standard deviation of a parameter is to take an estimate for the approximate extreme range and divide it by four. (For example, if crest elevation were thought to vary from –200mm to +200mm about a mean value, the range would be 400mm and the standard deviation would be 100mm.)

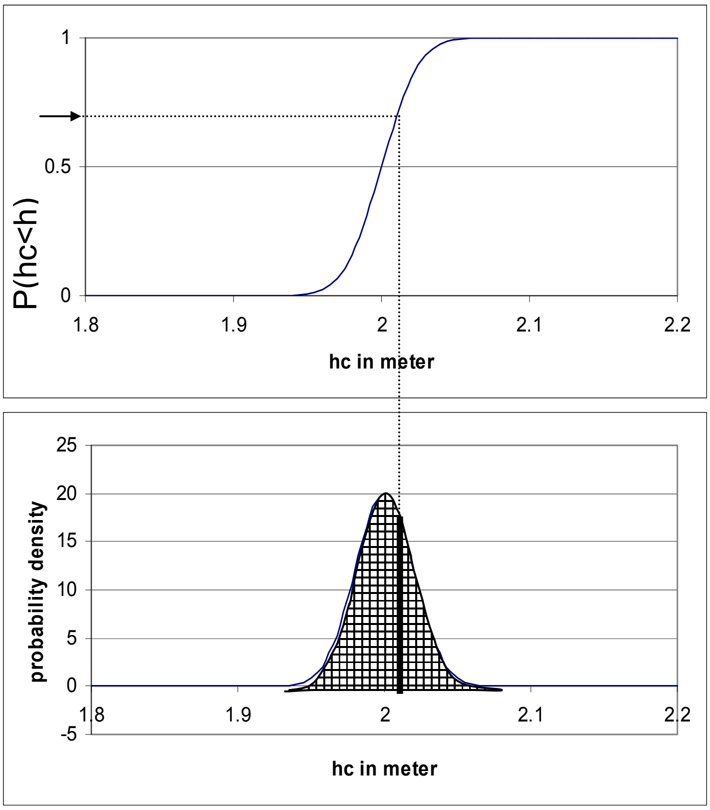


Figure 15 Use of fragility curves and corresponding probability density function in Monte Carlo analysis

Monte Carlo analysis enables the various input parameters (which can be seen as a joint probability distribution function) to be integrated over the total range of possible events to produce the values for Z. The approach that is adopted is as follows:

- Carry out many simulations (say between 1,000 and 10,000)
- For each simulation, the following steps are involved :
- For each variable: randomly draw a number between 0 and 1 from the distribution function, corresponding with one real value (square box) from the probability density function. This probability density function is the non-cumulative curve equivalent to the (cumulative probability) fragility curve (see Figure 15).
    - (a) Values corresponding with a high density (hatched area) are more likely to occur and are drawn more often.
    - (b) Calculate the value of Z for each set of randomly drawn variables and evaluate whether Z<0
- During the simulations count the number of times that Z<0
- Probability of failure = (no. of times Z<0)/(total no. of simulations)
- Draw a curve based on these results

4.3 An example of application of the methodology

This section outlines the approach which is appropriate for national level or broad scale flood risk assessment based on available data. A review was carried out in co-operation with practitioners to establish the most prominent failure modes of different flood and coastal defence types (HR Wallingford, 2004b). These failure modes are tabulated in section 2.2.

The following steps illustrate how fragility curves for coastal earth embankments can be created.

1. The main structure types were classified according to RASP High Level Method. (In the next steps the focus will be on type 6, coastal earth embankments.)
2. The main function of this type of defence is protecting against coastal flooding. (See Section 2.1 for a more detailed discussion of the main functions.)

3. A comprehensive overview of failure processes was made based partly on a desk study and partly on interviews with practitioners covering a wide variety of structure types. (The results from this investigation are discussed for earth embankments in section 2.2. The failure modes and the mutual relations are organised in a fault tree for earth embankments shown in Appendix 3.)

4. For coastal earth embankments failure due to wave overtopping followed by erosion of the embankment leading to breach was identified as the most prominent failure mode, see figure 16.

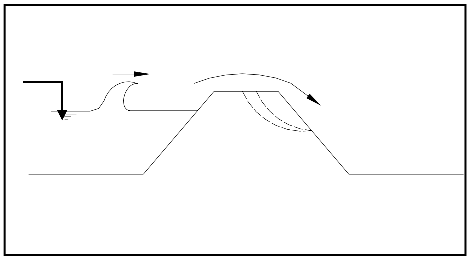


Figure 16 Failure due to overtopping

5. a) The information available for coastal earth embankments was identified; in this case the information came from the UK National Flood and Coastal Defence Database:
   - Type of revetment
   - Whether the embankment was narrow or wide (not quantified)
   - Condition grade 1 to 5, indicating excellent to very poor.

   b.) The damage to the rear-slope is caused by the wave overtopping discharge. The damage to the vegetation and erosion process of the rearslope can be expressed in terms of a process-based model for a corresponding critical wave overtopping discharge, according to Vrouwenvelder *et al*, 2001 or Buijs, 2003.

   c.) The key hydraulic loading was identified as wave overtopping. Expressing fragility in terms of the wave overtopping discharge was considered to be useful to amalgamate the water levels and wave conditions into one source variable.

6. The limit state function was calculated for this failure mode, $Z = q_c - q_a$, where q_c is the critical wave overtopping discharge for which breach occurs, *based* on strength of the grass on the rear slope, width of the embankment, erosion endurance of the embankment body, etc... (The details of the q_c model can be found in Vrouwenvelder *et al*, 2001 or Buijs, 2003. q_a is the actually occurring discharge which in a fragility curve is taken to be deterministic. The statistics of the loading are dealt with separately in the total risk assessment.)

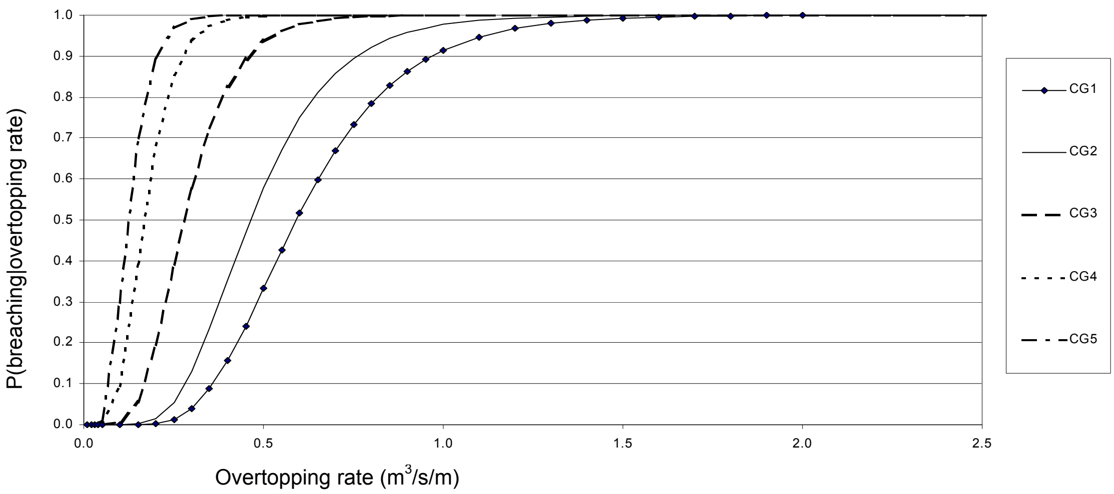
7. The parameters of the q_c model were set up with the statistical distribution functions, mean values and standard deviations, taken from Vrouwenvelder *et al*. (2001). (An example is given in Table 7 below. Considering the degree of knowledge about the parameters, larger variations should actually have been chosen. However, in this instance it was chosen to reflect this uncertainty in the form of upper and lower bands of the fragility curve.)

Here the quality of the revetment at the crest and of the inside slope was considered to be the most obvious physical characteristic described by the condition grades. The grass strength in the q_c model was taken as representative for the strength of the revetment on the crest and inside slope of the embankment. If the revetment is other than grass then the erosion endurance would need to be multiplied with an extra factor to take that effect into account. Finally, the range of coefficients associated with different degrees of erosion resistance were split up to reflect the five condition grades.

Table 7 Relevant parameters in the q_c model for coastal earth embankments in the national level flood risk assessment

		Distribution function	Mean value	Standard deviation (σ) or Variation coefficient (V)
		lognormal	7.5 (m)	σ = 0.2
	Wide		20 (m)	
Tan (angle inside slope)	Shallow	normal	0.5	V = 0.05
	Steep		0.25	
Condition grade	1	lognormal	1000000 (ms)	V = 0.30
	2		850000 (ms)	
	3		600000 (ms)	
	4		415000 (ms)	
	5		330000 (ms)	

8. Fragility curves were then calculated using the Monte Carlo method, making sure that sufficient simulations are performed. Figure 17 illustrates the results. The curves shown in the figures can be smoothed out by applying a large number of simulations during the Monte Carlo analysis.



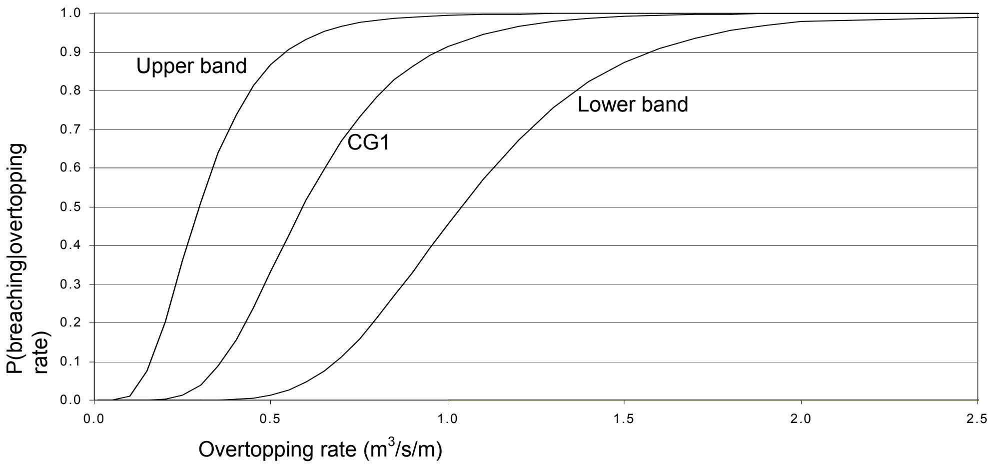


Figure 17 Example of fragility curves for broad scale risk assessments

Above fragility curves of 5 different condition grades (1=excellent, 5=very poor) for a narrow coastal impermeable embankment, turf front face and crest protection.

4.4 Example interpretation of fragility

In this section some examples of fragility are discussed for vertical wall structures and earth embankments.

4.4.1 Vertical wall structures

Figure 18 provides an example of fragility for a brick and masonry wall. The plot consists of two main parts:

1. Where the water level is lower than the crest level, failure is caused by toe scour and overturning of the structure followed by erosion of the embankment behind the structure. For fluvial situations, the toe scour depth is an increasing function with increasing local river water level and thus has a destabilising effect on the defence. On the other hand, an increasing water level stabilises overturning. The combination of those two effects determines whether the curve increases or decreases with a rising water level. In Figure

18 the stabilising water level apparently wins slightly over the destabilising scour depth for water levels lower than the crest level.

2. Where the water level exceeds the crest level, overflow occurs and causes erosion of the rear face of the embankment. The probability of breach starts to rise rapidly and at an overflow of 1.5 meters the structure is sure to fail.

All the vertical wall structures have a failure mode based on stability where the water level is smaller than the crest level. For gravity based walls that is overturning, and for sheet pile walls it is rotation. In all cases the probability of failure is rapidly dominated by the probability of overflow as soon as the water level exceeds the crest level. For coastal vertical seawalls, the destabilising toe scour is mainly caused by the local wave action. In these cases the fragility is conditional upon the significant wave height as well as the water level.

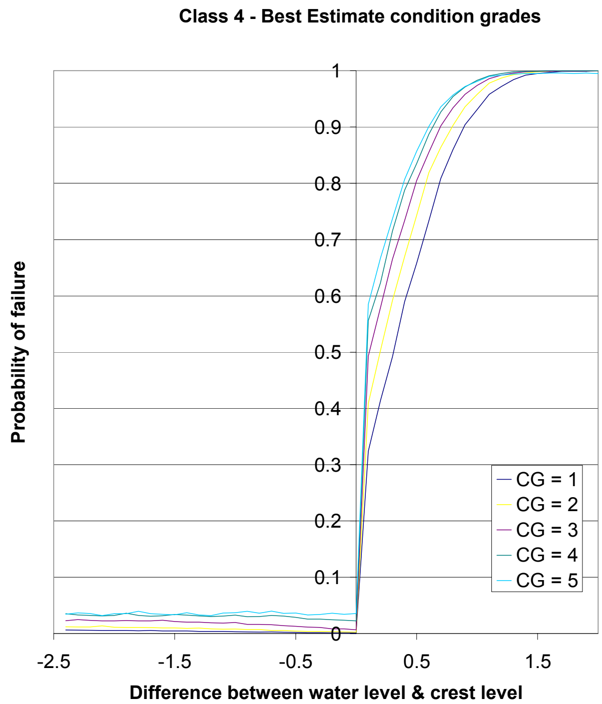


Figure 18 Class 4 is a Brick and Masonry wall, narrow embankment, front protection with fluvial loading

4.4.2 Earth embankments

Figure 19 provides the fragility of class 10 and class 31. The plots consist of the following failure modes:

- Piping, which mainly dominates the plot for fluvial embankments, e.g. class 10, where the water level is lower than the crest level. This failure mode is also contributes in the plot for class 31, but combines with failure due to wave overtopping.
- Wave overtopping and erosion of the rear face of the embankment. This failure mode does not feature in the plot for the fluvial embankment with negligible wave action. However, it significantly contributes to the probability of failure for water levels lower than the crest level in case of class 31, with wave action.
- Flowing over and erosion of the rear face of the embankment plays a role for water levels exceeding the crest level. In the coastal situation wave action has less impact during overflow situations, hence the drop in probabilities of failure.

These failure modes only represent a selection of a whole range of relevant failure processes. The fragility presented in the figure below is therefore indicative.

5. Conclusions and further research

5.1 Conclusions

5.1.1 Failure processes and physical process based models

This part of the project aimed to investigate the failure modes of a wide range of flood and coastal defence types in a desk study. In addition, interviews with practitioners served to gather experience-based knowledge about known defence failures

Process-based models are in most cases available but with various degrees of complexity, ranging from ‘one-line equations’ to detailed finite element models. Although a lot of research has already been done, these process-based models are subject to continuous improvement. For example the physics of geotechnical failure modes needs to be developed much further and validation is required of the simpler equations that are available against the more complex finite element models.

The different levels of detail of process-based models fit well into a tiered risk assessment structure – be it national, regional and defence scheme scale decision-making, or design projects with decision-making concerned with the feasibility, preliminary and detailed design stages. The underlying failure processes of coastal and flood defence types remain the same for all tiers. The choice of process-based model and number of failure modes can be tailored to the tier of decision-making and data availability in that tier.

Deterioration processes affect the properties of coastal and flood defences and therefore affect the failure modes of those defences. Deterioration can thus trigger failure modes not necessarily related to a storm event. Process-based models for deterioration processes are much less organised and developed than those for the main failure modes. Methods to account for the unpredictability in time of the deterioration source, (e.g. animal infestation), as well as the physical processes caused by it are still poorly understood.

The most prominent failure processes of the main defence types as concluded from the interviews with practitioners are given in table 7.

5.2 The applicability of the concept of fragility to capture the failure processes

An investigation was carried out into methods utilised to construct fragility for flood defences in other countries (mainly the Netherlands, Germany and USA) and other industries (nuclear, seismic and mechanical engineering).

Subsequently, structural reliability methods are recommended for constructing fragility for flood and coastal defences. These methods simulate defence failures based on the best available knowledge and data about the physical processes, aided by expert judgement to fill in the gaps. These processes are represented by process-based models that are conventionally applied in practice to assess the performance of structures.

The quality of the fragility results therefore hinges on the quality of:

- the underpinning process-based models;
- the representation of the uncertainties in those models and data;
- the data availability;
- the accuracy of the chosen calculation methods.

Although the structural reliability method is also subject to judgement-based influences, the underlying process-based or probabilistic models make the results more accessible to external scrutiny.

Two main issues were considered in the applicability of fragility to coastal and flood defences:

1. *The role of the concept of fragility in risk assessments containing different defence types.*

The concept of fragility is suitable to capture structural performance of flood and coastal defences. Fragility also allows insight in the sensitivity of the probability of failure to the characteristics of the defence. The quality of fragility depends on the quality of the process-based models.

Fragility is currently heavily founded on hydraulic loading conditions leading to flooding. Coastal and flood defence systems also contain elements that have functions other than delivering flood and coastal protection. Neglecting these other functions might underestimate the importance of certain defence types or point structures in the system. Also, fragility sometimes needs extra attention to ensure that the likelihood of the failure process correctly corresponds with the consequences in the risk term. A good example is coastal erosion, where failure of the coastal revetment can happen during a storm while the consequences are caused by an additional erosion process. The likelihood of the different developments in time of the erosion process must be considered as well.

Fragility maps the structural reliability of different failure modes and defence sections onto a uniform measure. This allows the comparison of the importance of different failure processes and defence sections. This can be used in tandem with information about the existing properties of the defence to efficiently inform decisions about maintenance, repair and improvement options.

Condition assessments should be linked to the failure modes of the coastal or flood defence. Rather than focusing on one dominant failure mode, the condition assessment should take all failure processes into account. In addition, the condition assessment should attempt to focus on the defence properties appearing in the process-based models. For visual condition assessments it is expected that the indicators used will have indirect relations with the properties relevant in the failure processes. These indirect relations should preferably be quantified as much as possible. The indirectness also reflects on the confidence about the quantification of the properties in the process-based models.

2. *To what extent the concept of fragility is applicable to process-based models associated with different defence types.*

The following comment is generally applicable - ‘as physical understanding of failure processes progresses, the quality of fragility improves’.

Even if good quality process-based models are available, it is clear that ways to construct fragility are not straightforward for all failure processes. Examples are geotechnical failure modes, failure modes between storms or vertical walls triggered by deterioration processes, and time-dependent processes in general.

The evaluation of the concept of fragility for defence point structures pointed out that point structures should be considered in the wider system-based context. Extreme local water levels are caused by several factors such as afflux, as well as the total capacity of the system of watercourses and the duration of the rainfall. Such an approach allows attention to be focused on the most influential defence point structures. After targeting the most important point structure the individual fragility can be investigated to get clues about how to improve it.

5.2.1 Generic fragility for the main defence types

Generic fragility for the main defence types was constructed. The steps to create fragility for a dominant failure mode as well as the data requirements have been given in TR 1. The detailed discussion of constructing fragility for the main defence types in the annexes of TR1 is provided in TR 2. This methodology captures the indicative failure modes identified in the review of failure processes in more detail and is fine-tuned to situations with low data availability The models, and e.g. failure mode dependencies, should therefore be revisited when moving towards more detailed assessments.
The approach described in TR2 demonstrates the process to generate a fragility curve, and provides a basis for future improvements of the fragility curves when more data becomes available, and for more detailed risk assessments.

5.3 Links to other projects and further research

This project has promoted close links with several other projects and enabled invaluable development in flood and coastal risk management. Three key links include;

- The Flood Risk Management Research Consortium (FRMRC) – especially in the development of work package 4.3 – the development of a structured asset inspection methodology to enable better informed asset management decisions for reducing flood risk. The concept of ‘failure modes’ – used by fragility methodology – has provided a focus and a framework around which to construct a revised condition assessment and inspection methodology for the purpose of assessing flood and coastal defence performance.

- Performance-based Asset Management System (PAMS) – fragility is a central element of the PAMS methodology. It is an integrated part of the asset risk and performance assessment at both high and detailed levels. This project has enabled a level of detail to be added beneath the RASP high level method already established and used in national flood risk assessment (NaFRA). In doing so it has brought the concept within the bounds of the regional and local practitioner.
- Thames Estuary 2100 – is demonstrating this regional level application of fragility through a PAMS – type model. Also a version of the inspection methodology that the work on fragility has helped to develop is being used to gather data to update the model, which in turn should – through iteration – lead to better quality outputs.

This application of fragility methodology to flood and coastal defence assessment is a new and rapidly developing area of research. Advances will continue to be made for example in the understanding of failure processes and deterioration – developing the process based models on which fragility curves are constructed. For this reason it is important to ensure that future dissemination should be as contemporary as possible.

6. References

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BS 8002: Part 2: 1994 *Code of practice for earth retaining structures*

7. Glossary of terms

Afflux
The maximum difference in water level, at a location upstream of a structure, if the structure were removed.

Asset system
In the context of flood risk management this means those assets that, as a whole, contribute to a reduction in the risk of flooding, or to maintaining the status quo, in the area at risk.

Coastal defences
Defences with a function to either protect against erosion or against flooding by the sea. Coastal defences with a function to protect against flooding will be referred to as coastal flood defence, coastal defences with a function to protect against erosion will be referred to as coastal protection.

Consequence
An impact such as economic, social or environmental damage/improvement that may result from a flood. May be expressed quantitatively (e.g. monetary value), by category (e.g. High, Medium, Low) or descriptively.

Defence system
Two or more defences acting to achieve common goals (e.g. maintaining flood protection to a floodplain area (or single flood cell) / community).

Failure
Exceedence of a defined performance threshold / performance indicator. It is additionally defined as occurring when the challenges to the system (of flood and coastal defence, or any part thereof) exceed its capacity to withstand them.

Failure mode
Description of one of any number of ways in which a defence or system may fail to meet a particular performance target/threshold.

Fault tree
Contains the different chains of events/failure modes leading to a top event representing the failure under analysis. The different events in the fault tree are expressed in boxes and are mutually connected through logical gates, e.g. OR, AND, etc.

Flood
A temporary ‘unwanted’ covering of land by water

Flood damage
Damage to receptors (buildings, infrastructure, goods), production and intangibles (life, cultural and ecological assets).

Flood defences
Flood defences are defined as defences protecting against flooding by the river or the sea.

Flood risk management
According to context, either action taken to mitigate risk, or the complete process of risk assessment, options appraisal and risk mitigation.

Fragility
The probability of failure of a particular defence or system given a load condition. Fragility can be expressed in the form of a curve when one loading condition is considered, in the form of fragility space when two loading conditions are considered or multidimensional fragility when more than three loading conditions are considered. Combined with descriptors of decay/deterioration, fragility functions enable future performance to be described.

FMECA - Failure Mode, Effects and Criticality Analysis
Failure Mode, Effects and Criticality Analysis is an analysis of all the ways in which a structure can fail organised in a cause consequence and effects diagram.

Hazard
A physical event, phenomenon or human activity with the *potential* to result in harm. A hazard does not necessarily lead to harm.

Likelihood
A general concept relating to the chance of an event occuring. Likelihood is generally expressed as a probability or a frequency.

Limit state
The boundary between failure and non-failure (Here the limit state is expressed by a limit state function, Z, which includes a model representing the strength, R, and the loading, S. Failure is defined when $Z<=0$.)

Load
Refers to environmental factors such as high river flows, water levels, wave heights and soil pressures to which the flooding and erosion system is subjected.

Logical gates
Logical gates are utilised to qualitatively represent the relations between failure modes in a fault tree. The *logical OR-gate* is applied when either one of two events can trigger the next step in the chain of failure events. This type of gate can be compared to a necklace of links, if one (or the weakest) link breaks the whole necklace 'fails'. Typical of this type of relation is the concept that the weakest link dominates the outcome; hence the highest probability of failure of the two events dominates the probability of the triggered event. The *logical AND-gate* is applied when two events are an absolute requirement to trigger the next event in the chain of failure events. The lowest probability of failure of the

two events dominates the probability of the triggered event. This type of gate can be compared to two lights in an electrical circuit which are applied in a parallel setting. Both lights must fail in order to disrupt the electrical current after the parallel circuit.

Monte Carlo
A level III probabilistic calculation method where a large number of simulations are performed (rule of thumb >1/Probability of failure). In each simulation, numbers are randomly drawn from the distribution functions associated with the parameters in the strength and loading models, subsequently the value of the limit state function is calculated for the joint draw. The number of times that Z is smaller than zero is divided by the total number of simulations to estimate the total probability of failure.

Non-structural failure
Failure of a flood or coastal defence to perform its function without damage to the structure, e.g. occurrence of high overtopping discharges of a flood defence leading to unacceptable damages to the assets in the hinterland without breach or collapse of the flood defence occurring.

Parameters
The parameters in a model are the "constants", chosen to represent the chosen context and scenario. In general the following types of parameters can be recognised:

- *Exact parameters* - which are universal constants, such as the mathematical constant: Pi (3.14259...).
- *Fixed parameters* - which are well determined by experiment and may be considered exact, such as the acceleration of gravity, g (approximately 9.81 m/s).
- *A -priori chosen parameters* - which are parameters that may be difficult to identify by calibration and so are assigned certain values. However, the values of such parameters are associated with uncertainty that must be estimated on the basis of a-priori experience, for example detailed experimental or field measurements
- *Calibration parameters* - which must be established to represent particular circumstances. They must be determined by calibration of model results for historical data on both input and outcome. The parameters are generally chosen to minimise the difference between model outcomes and measured data on the same outcomes. It is unlikely that the set of parameters required to achieve a "satisfactory" calibration is unique.

Performance
The creation or achievement of something that can be valued against some stated initial aim or objective, and also, the degree to which a process succeeds when evaluated against some stated aim or objective.

Performance indicator
The well articulated and measurable objectives of a particular project or policy. These may be detailed engineering performance indicators, such as acceptable

overtopping rates or rock stability, or more generic indicators such as public satisfaction.

Probability
A measure of the chance that an event will occur. The probability of an event is typically defined as the relative frequency of occurrence of that event, out of all possible events. Probability can be expressed as a fraction, % or a decimal. For example, the probability of obtaining a six with a shake of a fair dice is 1/6, 16% or 0.166. Probability is often expressed with reference to a time period, for example, annual exceedence probability.

Probabilistic calculation methods
Methods which numerically approximate the probability of failure. They are categorised as Level III, II or I, based on the way in which the probability of failure is calculated. Level III numerically integrates the probability density over the failure space (e.g. Monte Carlo). Level II transforms the parameters of the limit state function into the standard normal space and calculates the smallest distance between the limit state (Z=0) and the origin. Level I methods are safety factors conventionally known in civil engineering practice.

Probability density function (distribution)
Function which describes the probability of different values across the whole range of a variable (for example flood damage, extreme loads, particular storm conditions etc).

Receptor
Receptor refers to the entity that may be harmed (a person, property, habitat etc.). For example, in the event of heavy rainfall *(the source)* flood water may propagate across the flood plain *(the pathway)* and inundate housing *(the receptor)* that may suffer material damage *(the harm or consequence).* The vulnerability of a receptor can be modified by increasing its resilience to flooding.

Reliability of flood or coastal defences
Conventionally understood as the performance of flood or coastal defences as described by process-based models. In the context of a risk assessment that definition is extended to the probability that the flood or coastal defence does not fail (the complement of the probability of failure), where failure is defined using a limit state function with conventional process-based models representing the strength and loading models.

Residual risk
The risk (see ‘Risk’) that remains after risk management and mitigation. May include, for example, damage predicted to continue to occur during storm events of greater severity than the 100 to 1 annual chance event.

Resilience
The ability of a system/community/society/defence to react to and recover from the damaging effect of realised hazards.

Response (in context)
The reaction of a defence or system to environmental loading or changed policy.

Response function
Equation linking the reaction of a defence or system to the environmental loading conditions (e.g. overtopping formula) or changed policy.

Return period
The expected (mean) time (usually in years) between the exceedence of a particular extreme threshold. Return period is traditionally used to express the frequency of occurrence of an event, although it is often misunderstood as being a probability of occurrence.

Risk
Risk is a combination of the chance of a particular event, with the impact that the event would cause if it occurred. Risk therefore has two components – the chance (or *probability*) of an event occurring and the impact (or *consequence*) associated with that event. Risk is often measured or evaluated by: Risk = probability x consequence. The consequence of an event may be either desirable or undesirable. Generally, however, the flood and coastal defence community is concerned with protecting society and hence a *risk* is typically concerned with the likelihood of an undesirable consequence and our ability to manage or prevent it.

Risk analysis
A methodology to objectively determine risk by combining probabilities and consequences or, in other words, combining hazards and vulnerabilities.

Risk assessment
The process of judging risks which have been analysed.

Risk evaluation
Procedure to evaluate risks (e.g. specified by a risk analysis) balancing the reachable benefits by utilisation of source areas and flood-prone areas on the one hand with the potential damages and costs for mitigation measures on the other hand depending on individual or collective perception and values.

Risk management
The complete process of risk assessment, options appraisal and risk mitigation

Risk reduction - The reduction of the likelihood of harm, by either reduction in the probability of a flood occurring or a reduction in the exposure or vulnerability of the receptors.

Sensitivity
Refers to either: the resilience of a particular receptor to a given hazard. For example, frequent sea water flooding may have considerably greater impact on a fresh water habitat, than a brackish lagoon; or: the change in a result or conclusion arising from a specific perturbation in input values or assumptions.

Sensitivity Analysis
The identification at the beginning of the appraisal of those parameters which critically affect the choice between the identified alternative courses of action.

Scenario
A plausible description of how the future may develop, based on a coherent and internally consistent set of assumptions about key relationships and driving forces (e.g., rate of technology changes, prices). Scenarios are neither predictions nor forecasts. The results of scenarios (unlike forecasts) depend on the boundary conditions of the scenario.

Source
The origin of a hazard (for example, heavy rainfall, strong winds, surge, etc)

Statistic
A measurement of a variable of interest which is subject to random variation

Strategy (flood risk management)
Consistent/integrated set of measures, developed to achieve a certain goal – often responding to a scenario

Structural failure
Failure of the flood or coastal defence in the form of damage of the structure, e.g. breach

Susceptibility
The propensity of a particular receptor to experience harm.

System
An assembly of elements, and the interconnections between them, constituting a whole and generally characterised by its behaviour. Applied also for social and human systems.

Vulnerability – (system)
Characteristic of a system that describes its potential to be harmed. This can be defined as the product of susceptibility and value.

Uncertainty
A general concept that reflects our lack of sureness about something, ranging from just short of complete sureness to an almost complete lack of conviction about an outcome.

8. List of abbreviations

ALWC	Accelerated Low Water Corrosion
CFMP	Coastal Flood Management Plan
CIRIA	Construction Industry Research and Information Association
Defra	Department for the Environment, Food and Rural Affairs
EA	Environment Agency
EU	European Union
FCDPAG	Flood and Coastal Defence Project Appraisal Guidance
FMECA	Failure Mode, Effects and Criticality Analysis
GHG	Green House Gas
HCLPF	High Confidence Low Probability of Failure
HLM	High Level Method (RASP)
HLM+	High Level Method Plus (RASP)
ICE	Institution of Civil Engineers
ILM	Intermediate Level Method (RASP)
Lidar	Light detecting and ranging
NaFRA	National Flood Risk Assessment
NFCDD	National Flood and Coastal Defence Database
PAMS	Performance-based Asset Management System
Pf	Probability of failure
RASP	Risk Assessment of flood and coastal defence for Strategic Planning
SLS	Serviceability Limit State
SMP	Shoreline Management Plan
S-P-R-C	Source-Pathway-Receptor-Consequence
TAW	Technische Adviescommissie voor de Waterkeringen (Technical Advisory Commitee on Flood Defence for the Netherlands)
ULS	Ultimate Limit State
USACE	United States Army Corp of Engineers

Appendices

Appendix 1 Fragility curves in RASP Methodology

RASP High Level Methodology has been subject to further refinements. Below, firstly, the methodology is described as it was outlined in the initial RASP project. Secondly, the methodology is explained as it was refined in the 'High Level Methodology Plus'.

1.1 RASP High Level Methodology

How the above mentioned steps were originally approached in RASP High Level Methodology is explained below.

Flood defence types
The classification of the flood defences was based upon seven groups:

- Fluvial:
  - Vertical wall
  - Slope or embankment
  - High ground
  - Culverts
- Coastal
  - Vertical Seawall
  - Sloping seawall or embankment
  - Beach

Furthermore, the groups of defences were further subdivided for different revetment types, whether they were wide/narrow or whether they contained additional structures affecting the fragility curve of the defence.

Historical events
Analysis of historical events on a national scale was not part of the High Level Methodology at that stage of the development.

Key failure modes
The identification of key failure modes is based on the information coming from known historical events. As there is no such information nationally available at the moment, under the RASP project for the High Level Methodology fragility curves were developed for the following three different types of failure:

- *Probability of overtopping.* This is the probability of inundation due to overtopping discharges over the structure but no breach of the defence.

- *Probability of breach given overtopping.* This is the probability of breach occurring due to overtopping discharges that damage the defence ultimately leading to breach and inundation of the floodplain.

- *Probability of breach given no overtopping.* This is the probability of breach due to any other type of loading other than overtopping eventually leading to breach and inundation of the floodplain.

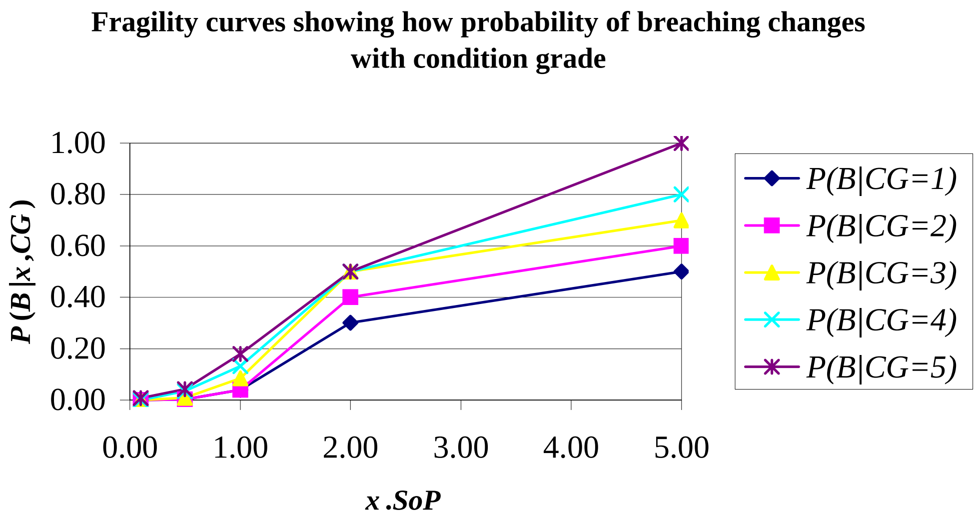


Figure 1.1. Family of fragility curves for the five different condition grades

Fragility curves
The fragility curves were defined as the probability of failure as a function of the ratio between a loading event and the Standard of Protection. This ratio therefore represents the severity of the loading event in proportion to the Standard of Protection, e.g. an event two times or three times as large as the event associated with the Standard of Protection. Then for different defence types (embankment/vertical wall, etc.) subdivided into sub-types (e.g. revetments, wide/narrow, etc.) the probability of failure, given this ratio, is estimated based on expert judgement.

For each defence (sub) type a family of fragility curves is derived expressing the differences in performance of five different condition grades, see Figure 1.1.

Loading conditions
The hydraulic boundary conditions corresponded with the Standard of Protection of the individual flood defences.

1.2 RASP High Level Methodology Plus

An improved NFCDD and the availability of more detailed topographic data have led to the development of the High Level Methodology Plus (or HLM+). This methodology is described below.

Flood defence types
No change in the classification of the flood defence (sub) types.

Historical events
No detailed analysis of historical events on a national scale.

Key failure modes
Indicator failure modes are chosen to underpin the generic fragility curves of the defence types. For coastal defences overtopping is taken as the indicator failure mode - as during storm situations some wave overtopping will always occur. The probability of overtopping given no breach is the complement of the probability of overtopping given breach and allows for the incorporation of damage due to discharge values for which the probability of breach is relatively small. For fluvial defences freeboard (water level – crest level) is taken to be the main loading parameter. For negative and lower positive freeboard values piping is taken as the indicator failure mode. Otherwise the probability of failure given water levels just below the crest level of the fluvial embankment does not contribute to risk at all, which is not a realistic representation. For higher positive freeboard values, overflow is taken to be the indicator failure mode.

Fragility curves
The fragility curves are based on the limit state functions involved with the three main indicator failure modes: overtopping, piping and overflow. The strength of the overtopping and overflow limit state functions depends on a critical discharge value. This critical discharge value represents the discharge value that will lead to breach of the defence. Different mean critical discharges have been adopted for the different defence types.

Loading conditions
In fluvial areas, instead of taking the Standard of Protection, a method is applied which predicts flood levels along the centre-line of rivers at 200 meter spacing and provides flood levels at 40 different return periods.

In coastal areas for each location a series of look-up tables is created which contains overtopping rates and return periods for a range of crest levels. The overtopping rates are based on several data sources and are generated using JOIN-SEA, taking dependence between wave conditions and water levels into account.

1.3 Fragility curves in RASP Intermediate Level Methodology

The RASP Intermediate Level Methodology is based on information from the NFCDD supplemented where available with more detailed information. The focus of the risk assessment is more regional and therefore has a less generic character than the High Level methodologies. How this translates itself into practice is presented below.

Flood defence types
In each region under assessment, the flood defence types that occur are determined. These flood defence types are classified according to those defined in the High Level Methodology.

Historical events
The regional historical damage or breach events are collected. These events point out the key failure mode for each flood defence type that has been identified. Risk assessments at the intermediate level are based on the key failure modes per region.

Key failure modes
As presented above, these key failure modes depend on the region that is under assessment. An example is the case study that has been done for Conwy in the context of the development of RASP Intermediate Level Methodology. The key failure modes that were identified for this study were:

> Embankments – Overtopping, piping, failure of rock armour revetment
> Beaches – crest retreat
> Vertical seawall – Collapse due to scour at the toe of the structure
> Dunes – wave run up

Fragility curves
For each of the above mentioned failure modes, existing models were used to predict values of the parameter representative for the loading part of the failure mode. For failure due to overtopping for instance overtopping discharges were calculated for the flood defences based on the equations according to Besley (1999). Failure probabilities linked to different overtopping discharge rates were estimated based on expert judgement.

Loading conditions
The loading conditions correspond with those used in the High Level Method + approach.

1.4 Fragility curves in RASP Detailed Level Methodology

The RASP Detailed Level Methodology is designed for more detailed, accurate risk assessment where the extra analysis is justified and where the data is available. This method has not been developed to the same extent as the HLM or ILM, and is restricted to specialist use at this stage.

Flood defence types
Detailed level risk assessments allow a local analysis based on the collection of data with respect to the characteristics of a structure and is therefore not based on generic shapes or descriptions.

Historical events
Knowledge of historical events is an important part of the assessment. Availability of these events provides the possibility to check whether the calculations to a certain extent point out the problem areas.

Key failure modes
The key failure modes result from an analysis of the historical events and rational analysis of the situation based on the models associated with the failure modes. To these failure modes most attention should be paid during the detailed risk

assessment. Apart from that, the detailed level risk assessments take a number of relevant failure modes into account for each flood defence section.

Fragility curves
Conditional probabilities of failure are derived for each failure mode based on the limit state functions and detailed models that describe the strength and loading components in these functions. Conditional probabilities of failure for different failure modes can also be combined to form one total conditional probability of failure. Calculations are based on methods such as FORM, SORM, Monte Carlo, Directional / importance Sampling.

Differentiation of the probability of failure given detailed combinations between water levels, significant wave heights, wave periods etc, can be made to enable a more detailed analysis of flooding scenarios. This leads to the use of multidimensional fragility rather than a fragility curve or surface.

The results from the calculations provide insight in the dominant failure mode and the main characteristics of the flood or coastal defence that contribute to the reliability of the defence.

Loading conditions
Data about local hydraulic boundary conditions are obtained from detailed local data-sets and numerical models of the local hydraulic climate.

Appendix 2 Key Failure Modes

<table>
<tr><th colspan="2">Flood and coastal defence type</th><th>Key Failure Modes</th></tr>
<tr><td colspan="2">Embankment / sloping seawall</td><td>• Erosion of crest and inside face leading to breach following overtopping (possibly induced by settlement)
• Piping, excessive seepage, breach or collapse following deterioration due to vermin infestation
• Breach following failure of foreign objects or weak spots caused by their presence</td></tr>
<tr><td colspan="2">Slope protection against erosion</td><td>• Structural failure following vandalism
• Toe erosion/foundation failure
• Slip failure due to instability or foundation failure
• Failure of slope drainage
• Damage by boats and barges
• Structural failure of inflexibility of rigid revetments placed on dynamic watercourses/coastlines</td></tr>
<tr><td colspan="2">Vertical wall structures</td><td>• Overtopping
• Toe erosion
• Failure of structural members (e.g. tie-rod or anchorage system)
• Structural failure due to wash out of fill following joint failure
• Structural failure following abrasion or corrosion</td></tr>
<tr><td rowspan="2">Beaches</td><td>Sand / Shingle Beach</td><td>Beach roll-back and erosion are natural cyclic processes rather than failure
Beaches fail when they do not perform their primary function (e.g. overtopping/ tidal flooding/erosion protection), although they may recover with time.
Key processes resulting in failure:
• Overtopping due to erosion/gullying/reduced energy dissipation following beach lowering
• Failure of control structures</td></tr>
<tr><td>Beach control / wave attenuation structures (ancillary coastal structures)</td><td>Failure is a failure of the system the structure directly or indirectly protects
Key failure modes:
• Progressive failure of timber groyne system following deterioration by rotting, abrasion, vandalism
• Ship impact</td></tr>
</table>

Key failure modes depend on the region that is under assessment and result from an analysis of historical events and a rational analysis of the situation based on the models associated with the failure modes. To these failure modes most attention should be paid during the detailed risk assessment. Detailed level risk assessments may take a number of relevant failure modes into account for each flood defence section. The table above lists those key failure modes identified by the consultation undertaken during the project and reported in the ‘Review of Flood and Coastal Defence Failures and Failure Processes’ (July 04) (see the project record for details).

Appendix 3 Fault Trees for the main defence types

Figure A3.1 ANCHORED SHEET PILE WALL FAILURE EVENT TREE

Equivalent to Rasp Type - *Class Nos. 43, 44, 52, 53,*

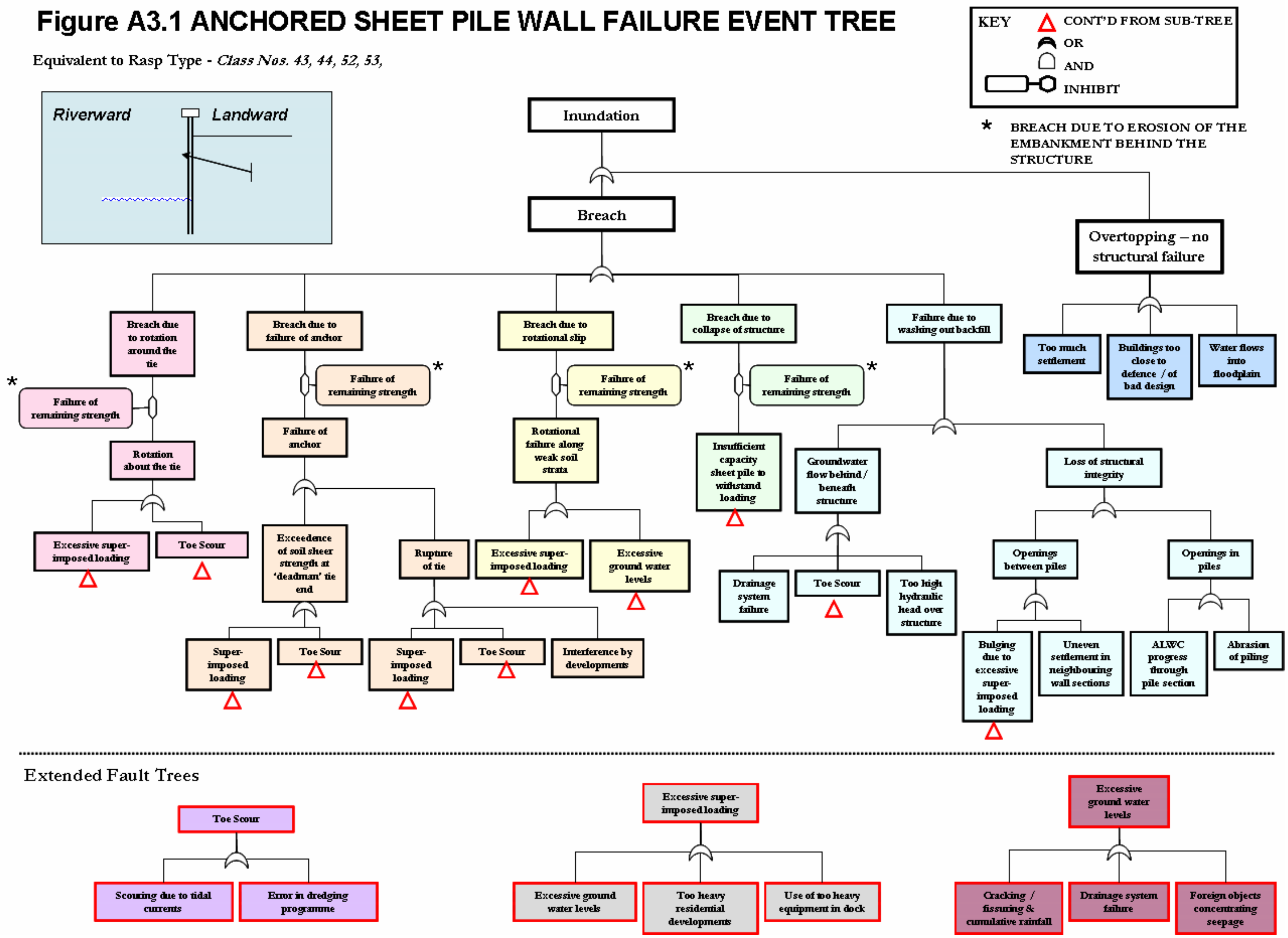
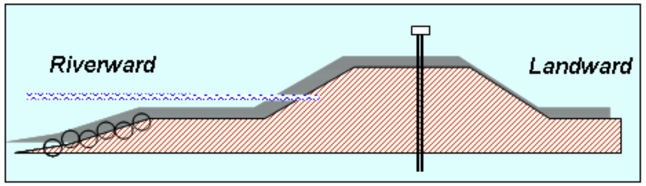


Figure A3.2 CANTILEVER SHEET PILE WALL FAILURE EVENT TREE

Equivalent to Rasp Type - *Class Nos. 7, 8, 9, 22, 23, 24*



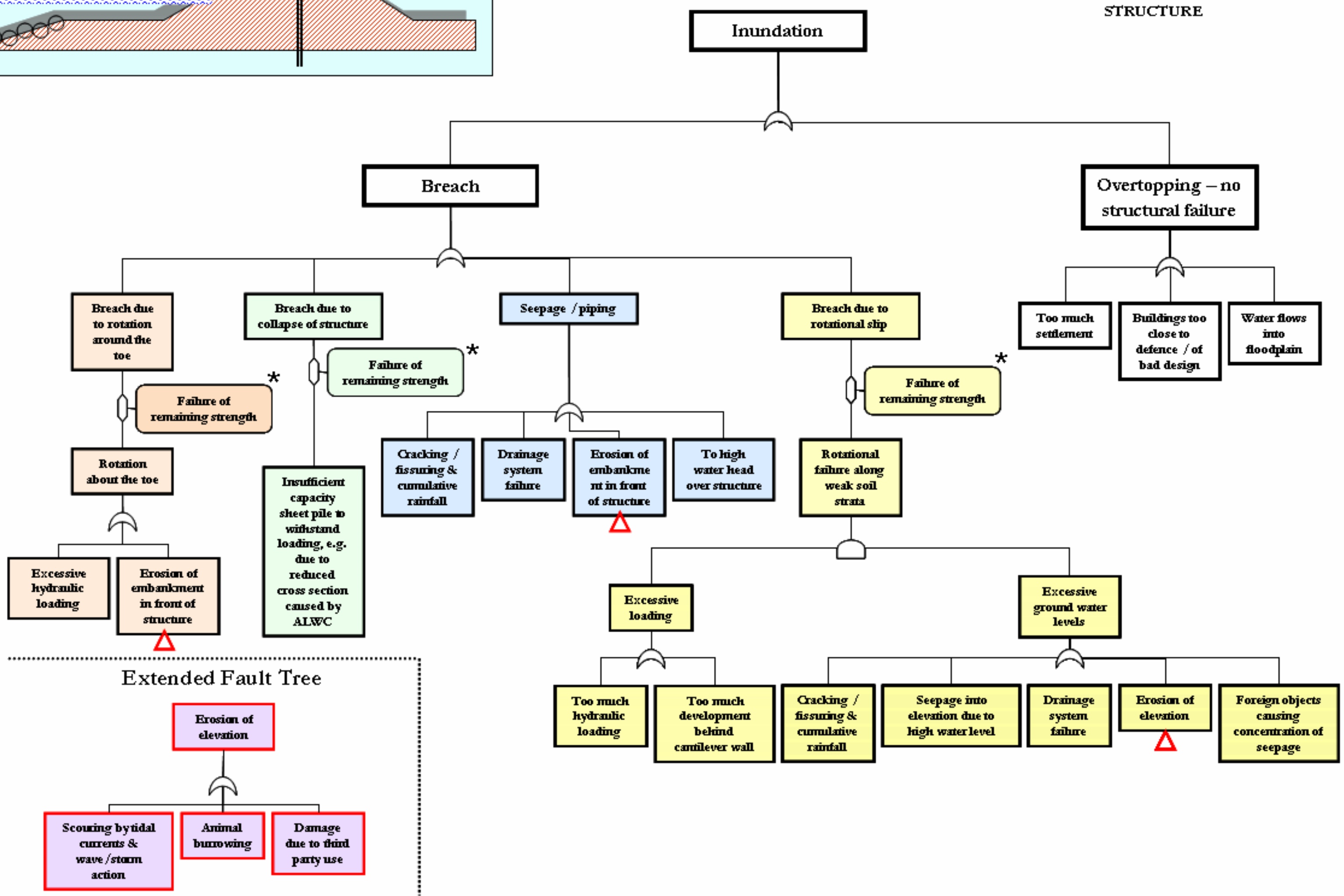
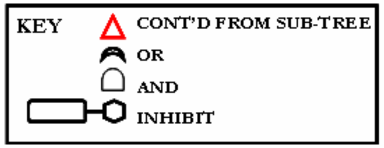


Figure A3.3a SINGLE CREST EMBANKMENT EVENT TREE

Equivalent to Rasp Type - *Class Nos. 10 to 19, 31 to 36, 45 to 51, 58 to 61.*



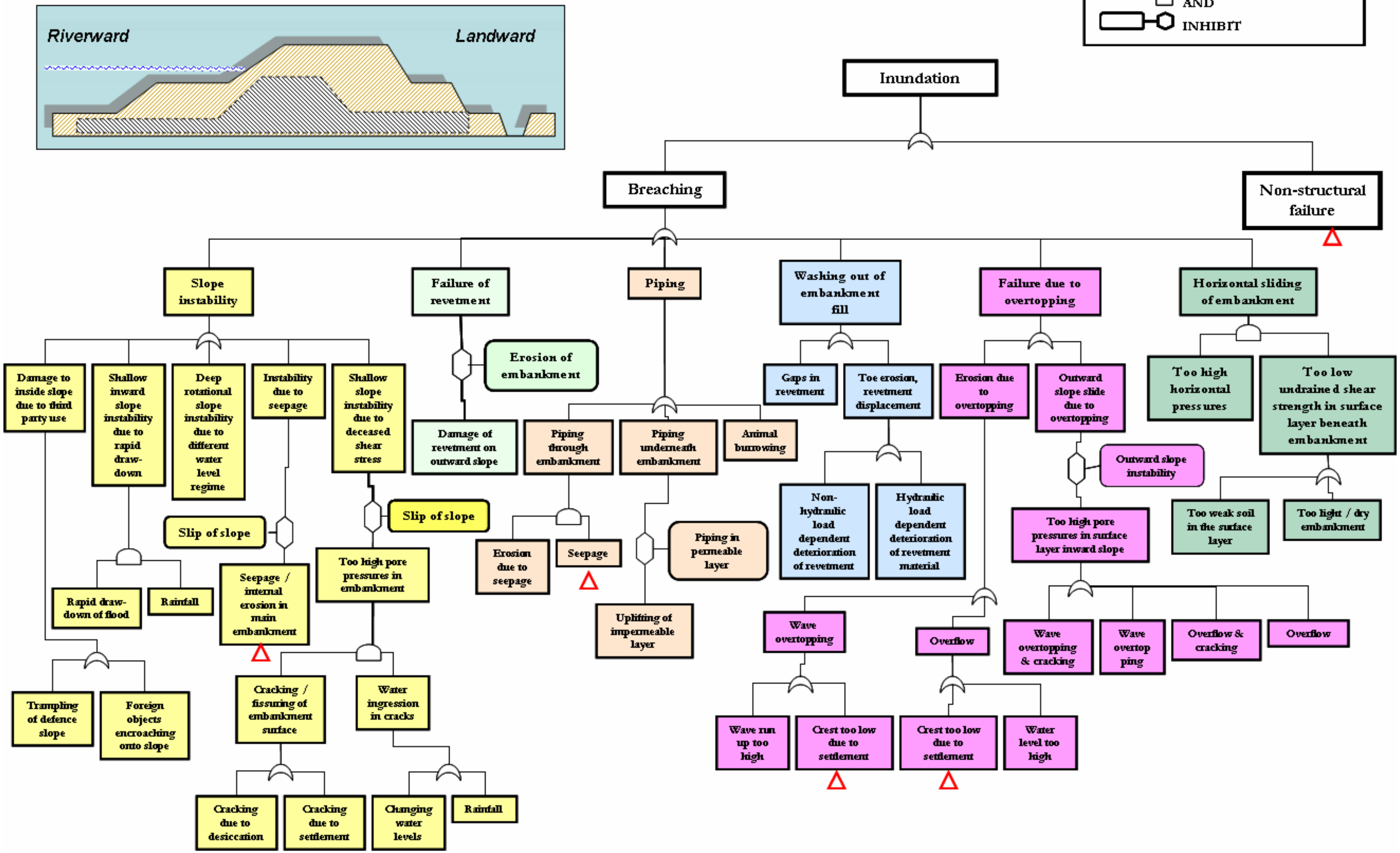


Figure A3.3b Extended Fault Trees for Single Crest Embankment

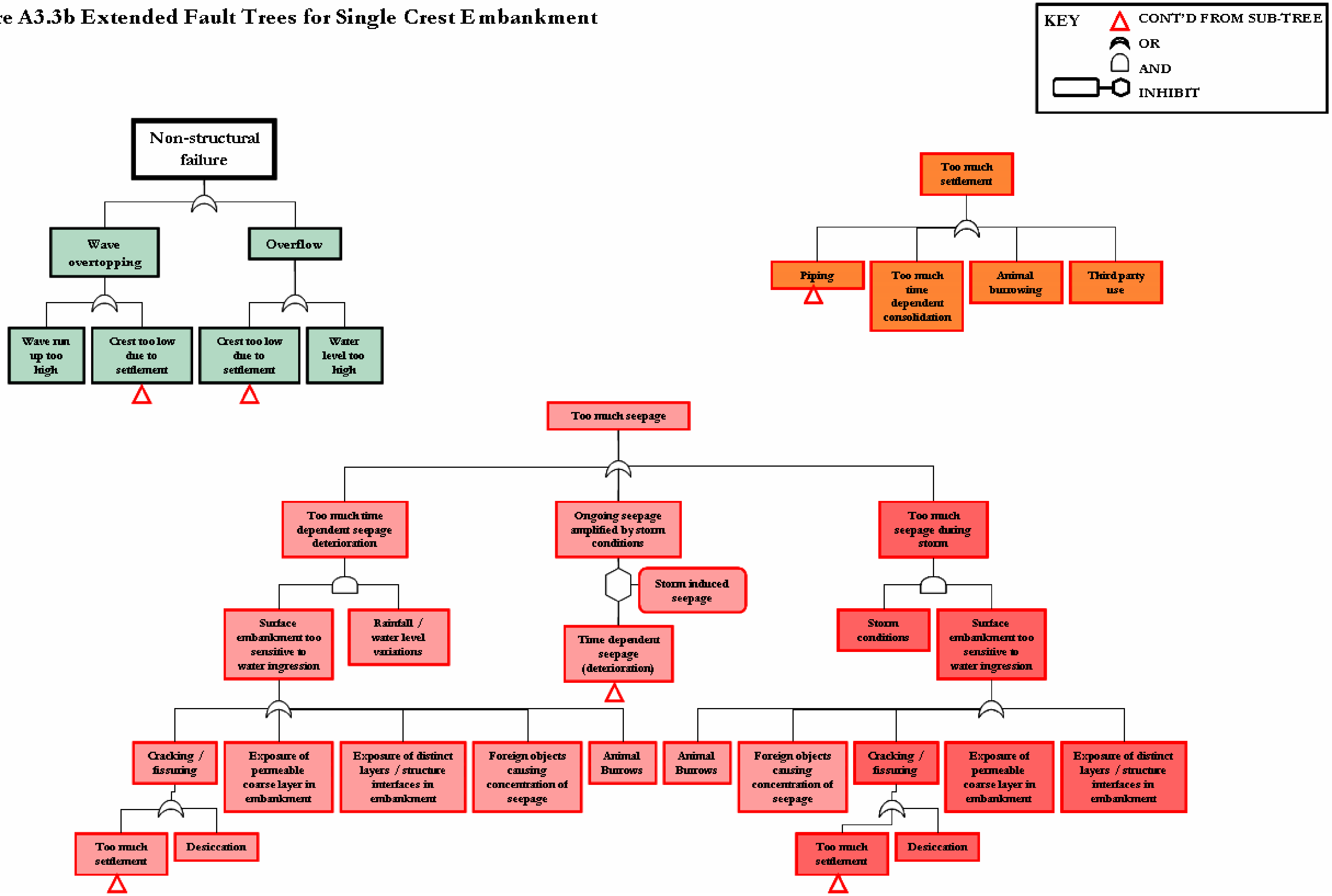


Figure A3.4 GRAVITY- BASED WALL (TYPE 1 - MASONRY) FAILURE EVENT TREE

Equivalent to Rasp Type *Class Nos. 1 to 6, 28 to 30, 39 to 42, 56 & 57*

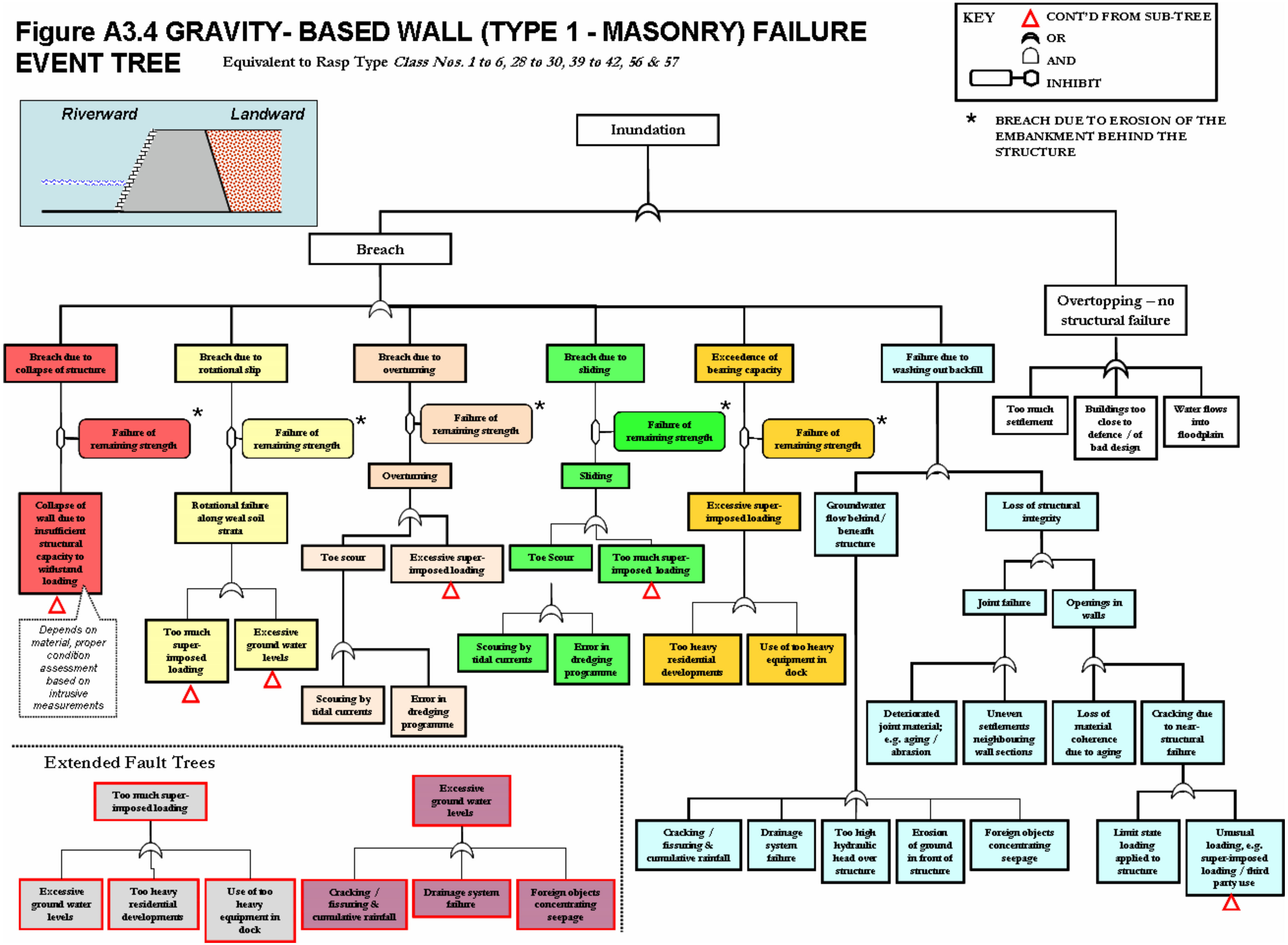
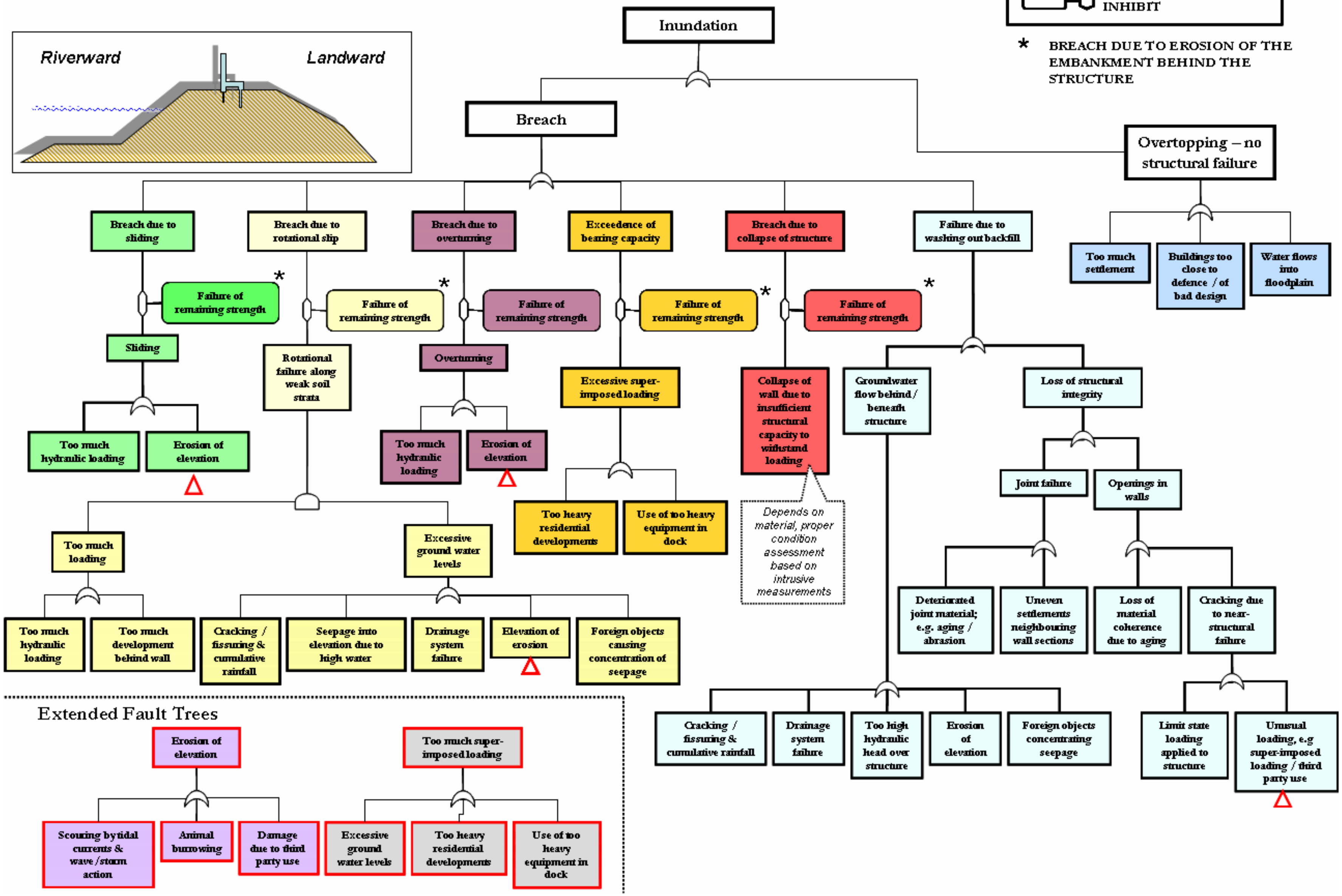


Figure A3.5 GRAVITY- BASED WALL (TYPE 2 - CONCRETE) FAILURE EVENT TREE

Equivalent to Rasp Type *Class Nos. 25 to 27, 54 & 55*



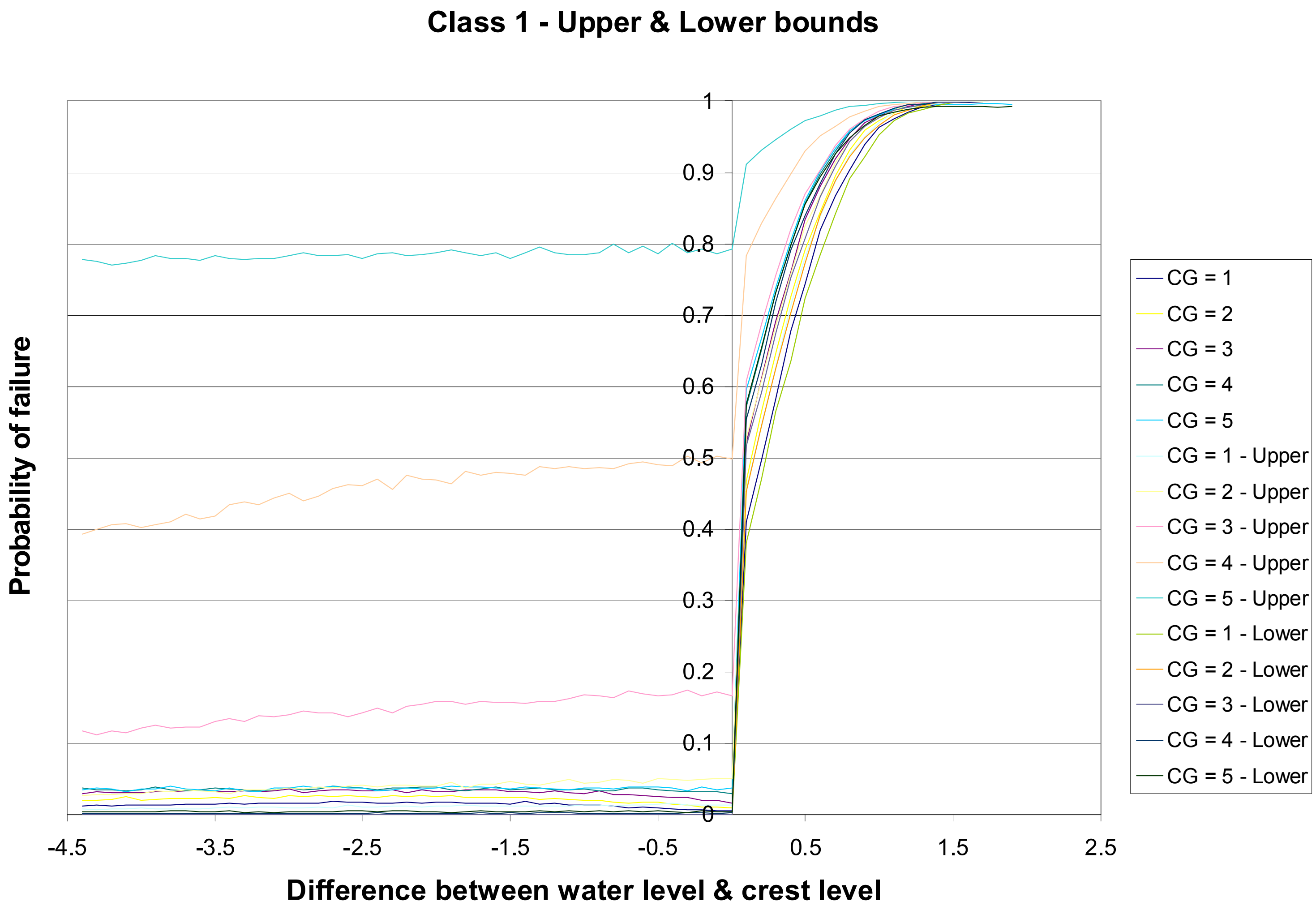
Appendix 4 Overview defence types with corresponding dominant failure modes and data requirements

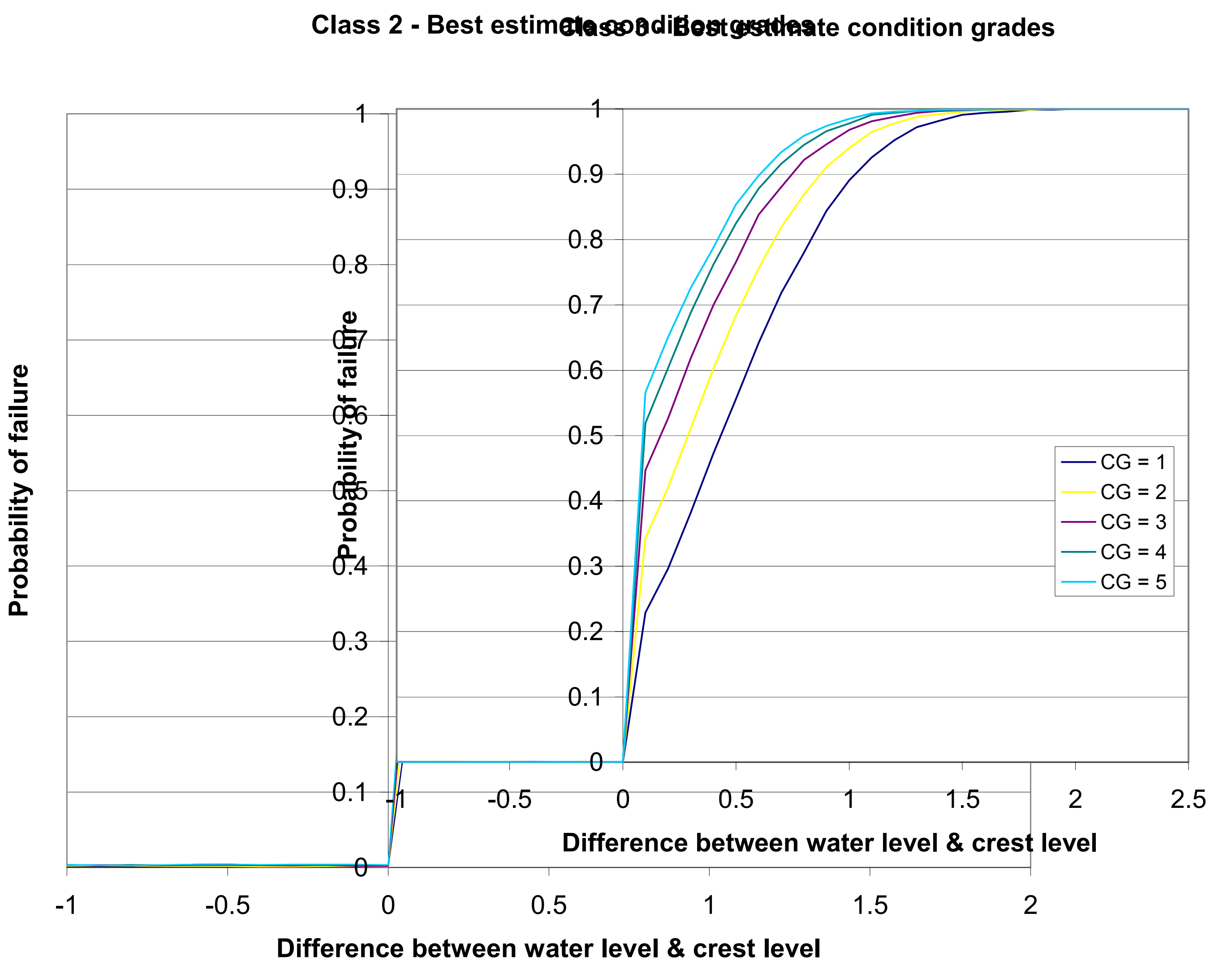
ClassNo	Description	Narrow/Wide	FP	CP	RP	Coastal/Fluvial	Type	Material	Dominant failure modes
1	Type 1, FP, Gabions	Narrow	Y			Fluv	Vertical Wall	Gabion	Overturning due to toe scour & erosion of earth bank
2	Type 1, CP, Gabions	Narrow	Y	Y		Fluv	Vertical Wall	Gabion	Overturning due to toe scour & erosion of earth bank
3	Type 1, RP, Gabions	Narrow	Y	Y	Y	Fluv	Vertical Wall	Gabion	Overturning due to toe scour & erosion of earth bank
4	Type 1, FP, B&M	Narrow	Y			Fluv	Vertical Wall	Brick & Masonry or Concrete	Overturning due to toe scour & erosion of earth bank
5	Type 1, CP, B&M	Narrow	Y	Y		Fluv	Vertical Wall	Brick & Masonry or Concrete	Overturning due to toe scour & erosion of earth bank
6	Type 1, RP, B&M	Narrow	Y	Y	Y	Fluv	Vertical Wall	Brick & Masonry or Concrete	Overturning due to toe scour & erosion of earth bank
7	Type 1, FP, Piles	Narrow	Y			Fluv	Vertical Wall	Sheet Piles	Rotational failure due to toe scour & erosion of earth bank
8	Type 1, CP, Piles	Narrow	Y	Y		Fluv	Vertical Wall	Sheet Piles	Rotational failure due to toe scour & erosion of earth bank
9	Type 1, RP, Piles	Narrow	Y	Y	Y	Fluv	Vertical Wall	Sheet Piles	Rotational failure due to toe scour & erosion of earth bank
10	Type 2, FP, Turf	Narrow				Fluv	Slopes or Embankments	Turf	Piping
11	Type 2, FP, Rigid	Narrow	Y			Fluv	Slopes or Embankments	Rigid	Piping
12	Type 2, CP, Rigid	Narrow	Y	Y		Fluv	Slopes or Embankments	Rigid	Piping
13	Type 2, RP, Rigid	Narrow	Y	Y	Y	Fluv	Slopes or Embankments	Rigid	Piping
14	Type 2, FP, Rip-rap	Narrow	Y			Fluv	Slopes or Embankments	Rip-rap	Piping
15	Type 2, CP, Rip-rap	Narrow	Y	Y		Fluv	Slopes or Embankments	Rip-rap	Piping
16	Type 2, RP, Rip-rap	Narrow	Y	Y	Y	Fluv	Slopes or Embankments	Rip-rap	Piping
17	Type 2, FP, Flexible	Narrow	Y			Fluv	Slopes or Embankments	Flexible	Piping
18	Type 2, CP, Flexible	Narrow	Y	Y		Fluv	Slopes or Embankments	Flexible	Piping
19	Type 2, RP, Flexible	Narrow	Y	Y	Y	Fluv	Slopes or Embankments	Flexible	Piping
20	Type 3, High Ground	-				Fluv	High Ground		-
21	Type 4, Culverts	-				Fluv	Culvert		
22	Type 5, FP, Piles	Narrow	Y			Coas	Vertical walls	Sheet piles	Rotational failure due to toe scour & erosion of earth bank
23	Type 5, CP, Piles	Narrow	Y	Y		Coas	Vertical walls	Sheet piles	Rotational failure due to toe scour & erosion of earth bank
24	Type 5, RP, Piles	Narrow	Y	Y	Y	Coas	Vertical walls	Sheet piles	Rotational failure due to toe scour & erosion of earth bank
25	Type 5, FP, Conc	Narrow	Y			Coas	Vertical walls	Concrete	Overturning due to toe scour & erosion of earth bank
26	Type 5, CP, Conc	Narrow	Y	Y		Coas	Vertical walls	Concrete	Overturning due to toe scour & erosion of earth bank
27	Type 5, RP, Conc	Narrow	Y	Y	Y	Coas	Vertical walls	Concrete	Overturning due to toe scour & erosion of earth bank
28	Type 5, FP, B&M	Narrow	Y			Coas	Vertical walls	Brick & Masonry	Overturning due to toe scour & erosion of earth bank
29	Type 5, CP, B&M	Narrow	Y	Y		Coas	Vertical walls	Brick & Masonry	Overturning due to toe scour & erosion of earth bank
30	Type 5, RP, B&M	Narrow	Y	Y	Y	Coas	Vertical walls	Brick & Masonry	Overturning due to toe scour & erosion of earth bank
31	Type 6, FP, Perm	Narrow	Y			Coas	Dykes or embankments	Permeable revetment	Piping
32	Type 6, CP, Perm	Narrow	Y	Y		Coas	Dykes or embankments	Permeable revetment	Piping
33	Type 6, RP, Perm	Narrow	Y	Y	Y	Coas	Dykes or embankments	Permeable revetment	Piping
34	Type 6, FP, Imperm	Narrow	Y			Coas	Dykes or embankments	Impermeable revetment	Piping
35	Type 6, CP, Imperm	Narrow	Y	Y		Coas	Dykes or embankments	Impermeable revetment	Piping
36	Type 6, RP, Imperm	Narrow	Y	Y	Y	Coas	Dykes or embankments	Impermeable revetment	Piping
37	Type 7, Dune	-				Coas	Beaches		Exceedance of crest width
38	Type 7, Shingle	-				Coas	Beaches		Exceedance of crest width
39	Type 1, W, FP, Gabions	Wide	Y			Fluv	Vertical Wall	Gabions	Overturning due to toe scour & erosion of earth bank
40	Type 1, W, CP, Gabions	Wide	Y	Y		Fluv	Vertical Wall	Gabions	Overturning due to toe scour & erosion of earth bank
41	Type 1, W, FP, B&M	Wide	Y			Fluv	Vertical Wall	Brick & Masonry or Concrete	Overturning due to toe scour & erosion of earth bank
42	Type 1, W, CP, B&M	Wide	Y	Y		Fluv	Vertical Wall	Brick & Masonry or Concrete	Overturning due to toe scour & erosion of earth bank
43	Type 1, W, FP, Piles	Wide	Y			Fluv	Vertical Wall	Sheet piles	Rotational failure due to toe scour & erosion of earth bank
44	Type 1, W, CP, Piles	Wide	Y	Y		Fluv	Vertical Wall	Sheet piles	Rotational failure due to toe scour & erosion of earth bank
45	Type 2, W, FP, Turf	Wide				Fluv	Slopes or Embankments	Turf	Piping
46	Type 2, W, FP, Rigid	Wide	Y			Fluv	Slopes or Embankments	Rigid	Piping
47	Type 2, W, CP, Rigid	Wide	Y	Y		Fluv	Slopes or Embankments	Rigid	Piping
48	Type 2, W, FP, Rip-rap	Wide	Y			Fluv	Slopes or Embankments	Rip-rap	Piping
49	Type 2, W, CP, Rip-rap	Wide	Y	Y		Fluv	Slopes or Embankments	Rip-rap	Piping
50	Type 2, W, FP, Flexible	Wide	Y			Fluv	Slopes or Embankments	Flexible	Piping
51	Type 2, W, CP, Flexible	Wide	Y	Y		Fluv	Slopes or Embankments	Flexible	Piping
52	Type 5, W, FP, Piles	Wide	Y			Coas	Vertical walls	Sheet piles	Rotational failure due to toe scour & erosion of earth bank
53	Type 5, W, CP, Piles	Wide	Y	Y		Coas	Vertical walls	Sheet piles	Rotational failure due to toe scour & erosion of earth bank
54	Type 5, W, FP, Conc	Wide	Y			Coas	Vertical walls	Concrete	Overturning due to toe scour & erosion of earth bank
55	Type 5, W, CP, Conc	Wide	Y	Y		Coas	Vertical walls	Concrete	Overturning due to toe scour & erosion of earth bank
56	Type 5, W, FP, B&M	Wide	Y			Coas	Vertical walls	Brick & Masonry	Overturning due to toe scour & erosion of earth bank
57	Type 5, W, CP, B&M	Wide	Y	Y		Coas	Vertical walls	Brick & Masonry	Overturning due to toe scour & erosion of earth bank
58	Type 6, W, FP, Perm	Wide	Y			Coas	Dykes or embankments	Permeable revetment	Piping
59	Type 6, W, CP, Perm	Wide	Y	Y		Coas	Dykes or embankments	Permeable revetment	Piping
60	Type 6, W, FP, Imperm	Wide	Y			Coas	Dykes or embankments	Impermeable revetment	Piping
61	Type 6, W, CP, Imperm	Wide	Y	Y		Coas	Dykes or embankments	Impermeable revetment	Piping

FP = front face protection, CP = crest protection, RP = rear face protection, W = wide

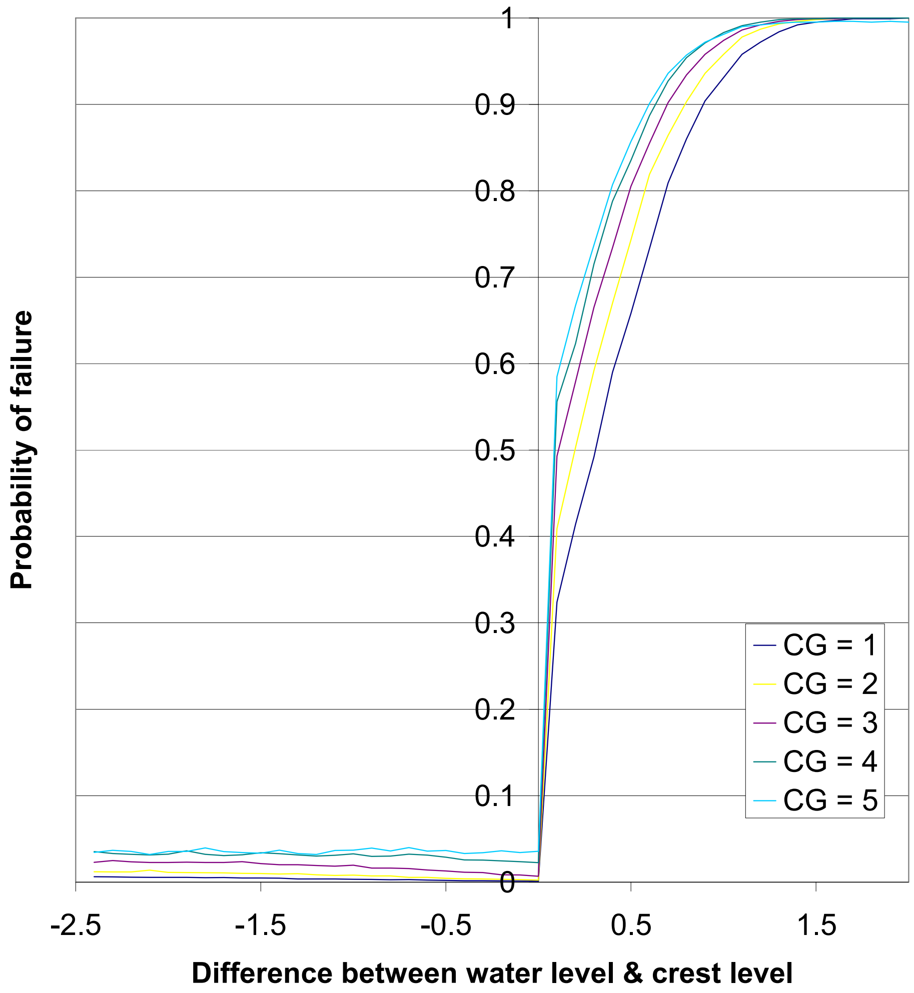
Symbol	Dimension	Description	Statistical distribution function	Mean value	stdv (=s) or variation coefficient (=v)
h	[m]	water level (with respect to the bottom level)	deterministic in fragility	variable	variable
Hs	[m]	significant wave height	deterministic in fragility	variable	variable
Tp	[s]	peak wave period	deterministic in fragility	variable	variable
hc	[m]	crest level (with respect to the bottom level)	normal	4.5	V = 0.1
cw	[m]	crest width	lognormal	variable	V = 0.25
tano	[-]	tan outside slope	normal	0.33	V = 0.05
tani	[-]	tan inside slope	normal	0.33	V = 0.05
cg	[ms]	erosion strength grass	lognormal	1000000	V = 0.3
cRK	[ms]	erosion strength core	lognormal	34000	V = 0.3
dw	[m]	depth grass roots	lognormal	0.2	V = 0.2
Pt	[-]	pulsating percentage	deterministic	0.5 (wave overtop) / 1 (flowing over)	-
r_i	[m]	roughness inside slope	lognormal	0.015	V = 0.01
ts	[h]	storm duration	lognormal	12 (fluvial) / 7 (coastal)	V = 12
m_qe	[-]	model uncertainty erosion model	lognormal	depends on class / condition grade	V = 0.1
r_o	[-]	roughness outside slope	lognormal	1	s = 0.01
beta	[°]	obliqueness waves	normal	0	s = 1
A	[-]	coefficient Owen's model	lognormal	0.0109	V = 0.1
B	[-]	idem	lognormal	28.7	V = 0.2
m_qo	[-]	model uncertainty owen's model	lognormal	1	V = 0.1
Dimp	[m]	thickness impermeable layers	normal	3	V = 0.3
gamma_wet	[kN/m^3]	saturated density of the soil	normal	18	0.05
gamma_w	[kN/m^3]	density of the water	deterministic	10	-
fg	[m]	depth ground water level below ground	deterministic	0.5	-
Lv	[m]	vertical seepage length	normal	0	s = 0.1
Lh	[m]	horizontal seepage length	normal	depends on class / condition grade	V = 0.2
cT	[-]	Creep ratio, Terzaghi	lognormal	depends on class / condition grade	V = 0.05
m_t	[-]	model uncertainty Terzaghi	lognormal	1	V = 0.1
riv	[-]	river or coast scour model	deterministic	0 (coastal) / 1 (fluvial)	-
H_s	[m]	height structure between ground level and bottom level	normal	4.5	V = 0.1
d	[m]	depth toe	normal	1.5	V = 0.1
Ka	[-]	coefficient horizontal grain stress; active	lognormal	0.33	
Kp	[-]	coefficient horizontal grain stress; passive	lognormal	3	
d_a	[m]	depth anchors	normal	0.8	V = 0.01
mspar_R	[-]	model uncertainty rotation anchored sheet pile - R	lognormal	1	V = 0.1
mspar_S	[-]	model uncertainty rotation anchored sheet pile - S	lognormal	1	V = 0.1
angle	[°]	angle of inclination anchors	normal	30	s = 5
no_anch	[-]	average number of anchors per stretching meter	det	1	-
rad	[m]	radius of anchors	lognormal	0.06	V = 0.01
mspas_R	[-]	model uncertainty anchored sheet pile snapping - R	lognormal	1	V = 0.1
mspas_S	[-]	model uncertainty anchored sheet pile snapping - S	lognormal	1	V = 0.1
mspcr_R	[-]	model uncertainty cantilever sheet pile rotation - R	lognormal	1	V = 0.1
mspcr_S	[-]	model uncertainty cantilever sheet pile rotation - S	lognormal	1	V = 0.1
H_c	[m]	total height gravity based structure	normal	6	V = 0.1
Ba	[m]	base gravity based structure	normal	2	V = 0.1
gamma_c	[kN/m^3]	density material of gravity based structure	lognormal	depends on class	V = 0.15
delta	[°]	friction angle	normal	40	V = 0.1
mgbo_R	[-]	model uncertainty gravity-based wall sliding - R	lognormal	1	V = 0.1
mgbo_S	[-]	model uncertainty gravity-based wall sliding - S	lognormal	1	V = 0.1
mgbo_R	[-]	model uncertainty gravity-based wall overturning - R	lognormal	1	V = 0.1
mgbo_S	[-]	model uncertainty gravity-based wall overturning - S	lognormal	1	V = 0.1
m_shw	[-]	model uncertainty width shingle beach	lognormal	1	V = 0.1
sh_width	[m]	shingle beach width	normal	15	V=0.25
Db	[m]	effective beach width	normal	depends on condition grade	V=0.26
mshret	[-]	model uncertainty shingle retreat	lognormal	1	V = 0.1
D50	[m]	D50 shingle	lognormal	depends on class	V = 0.1
Q_ac_sh	[m^3/s]	acceptable overtopping shingle beach	deterministic	1	-
m_q_sh	[-]	model uncertainty overtopping shingle	lognormal	1	V = 0.1
betar	[°]	angle oblique waves for reduction factor	normal	0	s = 1
gamma_s1	[kN/m^3]	saturated density soil behind vertical walls	normal	18	V = 0.1

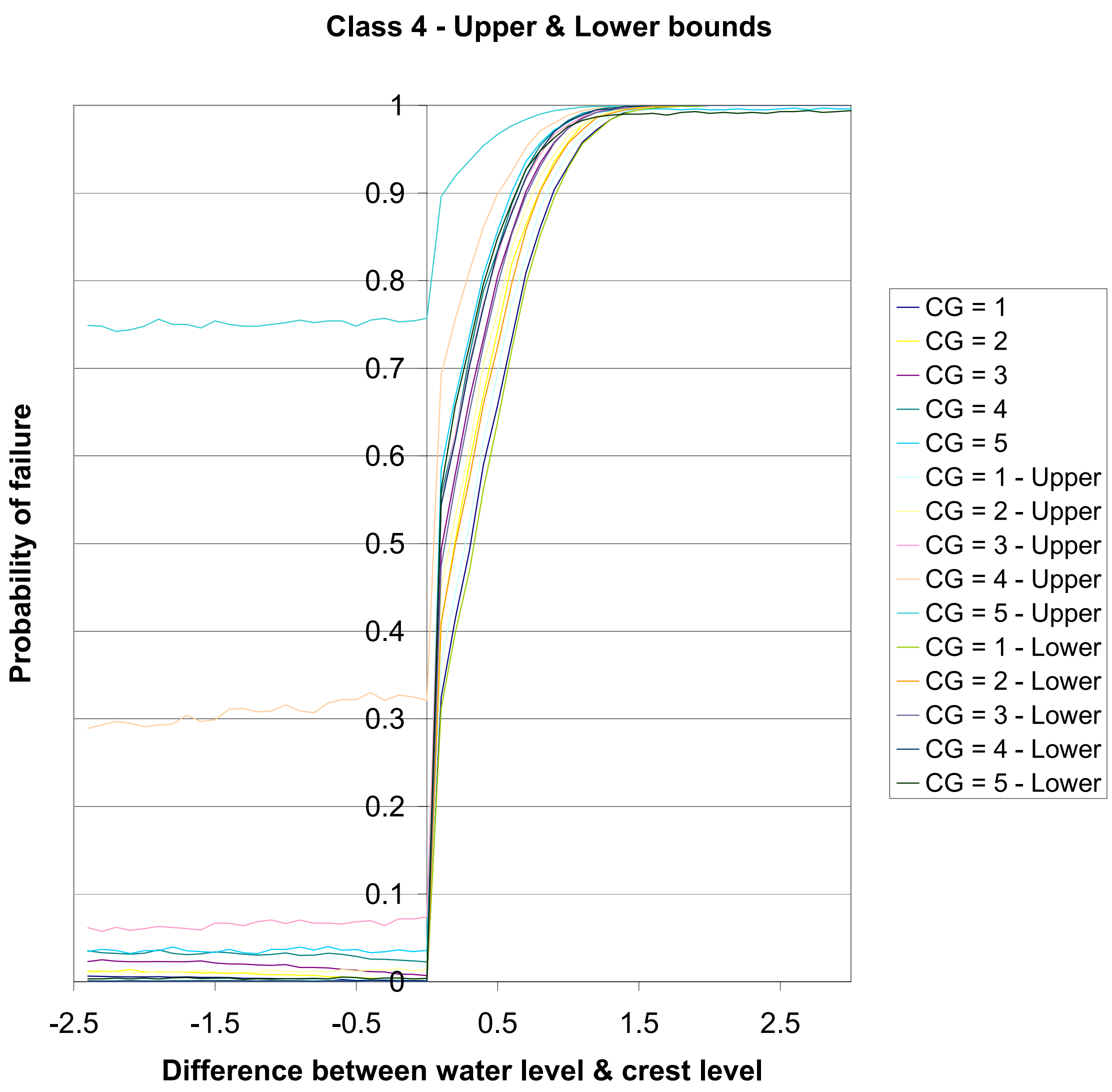
Appendix 5 Fragility curves for strategic level assessment


Class 1 - Upper & Lower bounds
Probability of failure
Difference between water level & crest level
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
-4.5
-3.5
-2.5
-1.5
-0.5
0.5
1.5
2.5
CG = 1
CG = 2
CG = 3
CG = 4
CG = 5
CG = 1 - Upper
CG = 2 - Upper
CG = 3 - Upper
CG = 4 - Upper
CG = 5 - Upper
CG = 1 - Lower
CG = 2 - Lower
CG = 3 - Lower
CG = 4 - Lower
CG = 5 - Lower

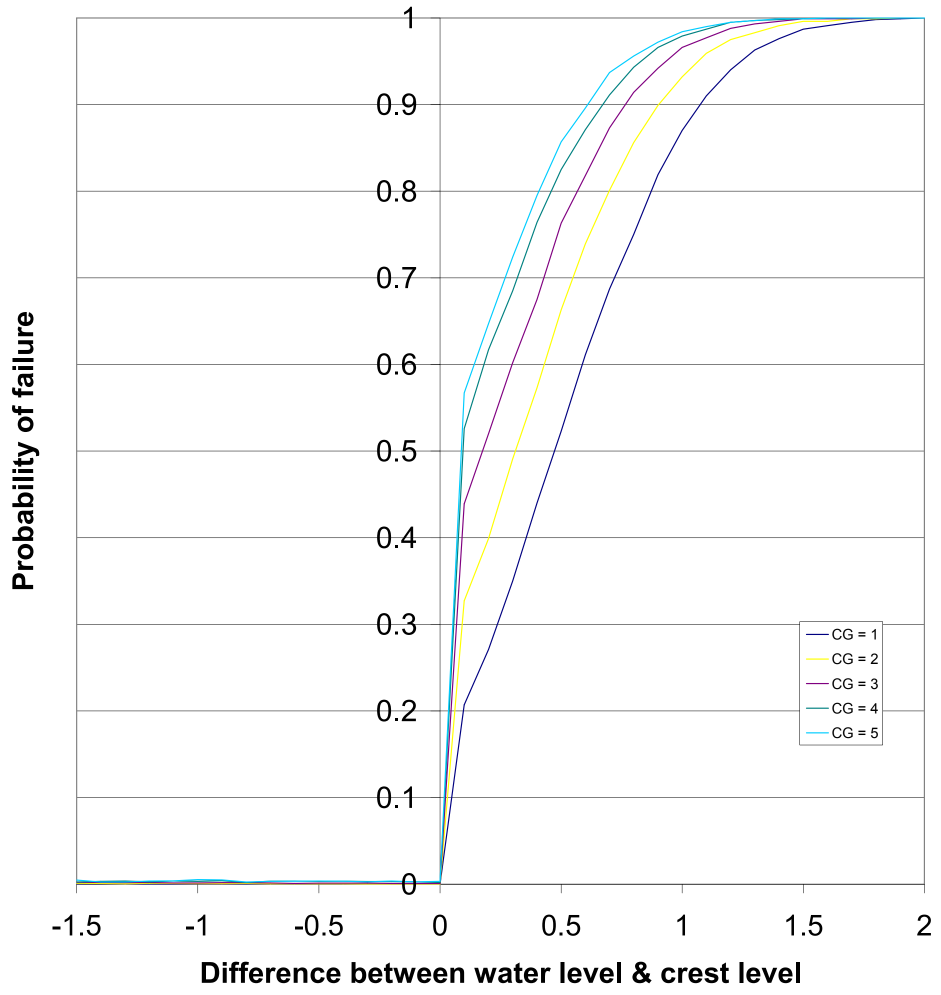

Class 2 - Best estimate condition grades
Class 3 - Best estimate condition grades
Probability of failure
Probability of failure
CG = 1
CG = 2
CG = 3
CG = 4
CG = 5
Difference between water level & crest level
Difference between water level & crest level

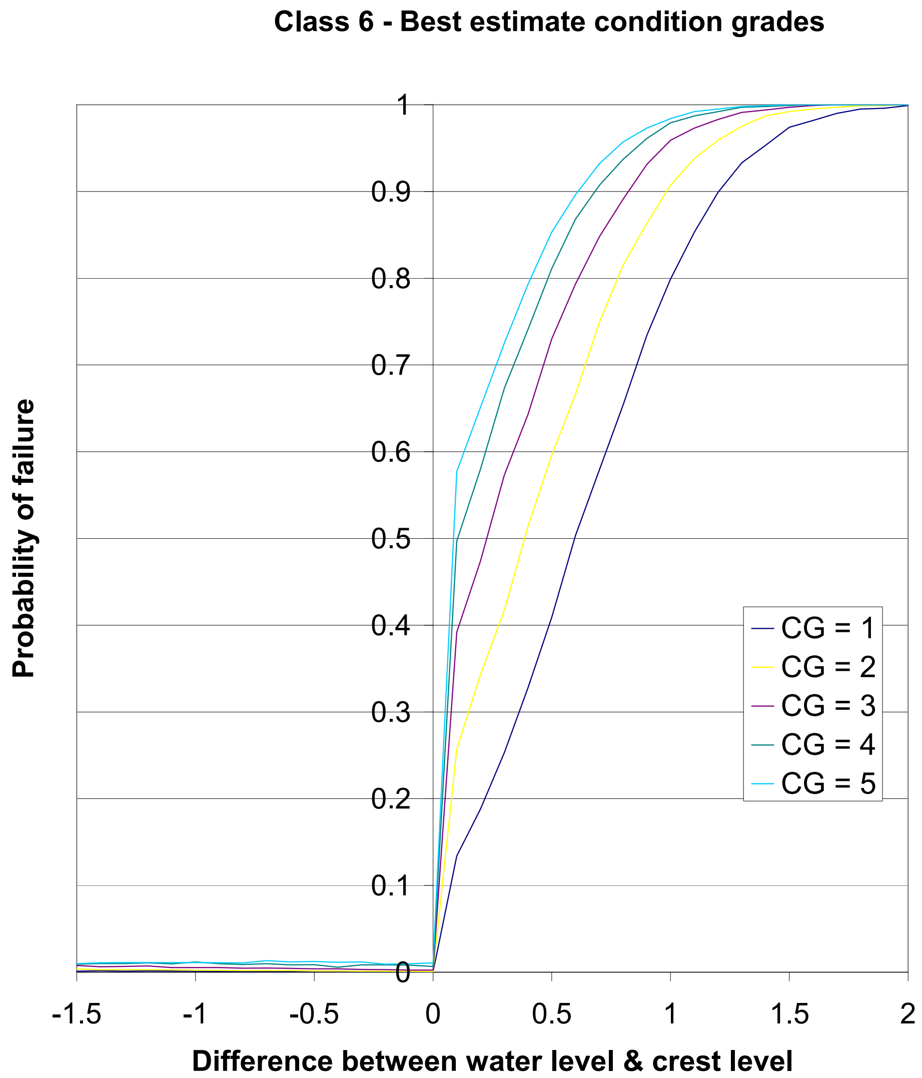
Class 4 - Best Estimate condition grades



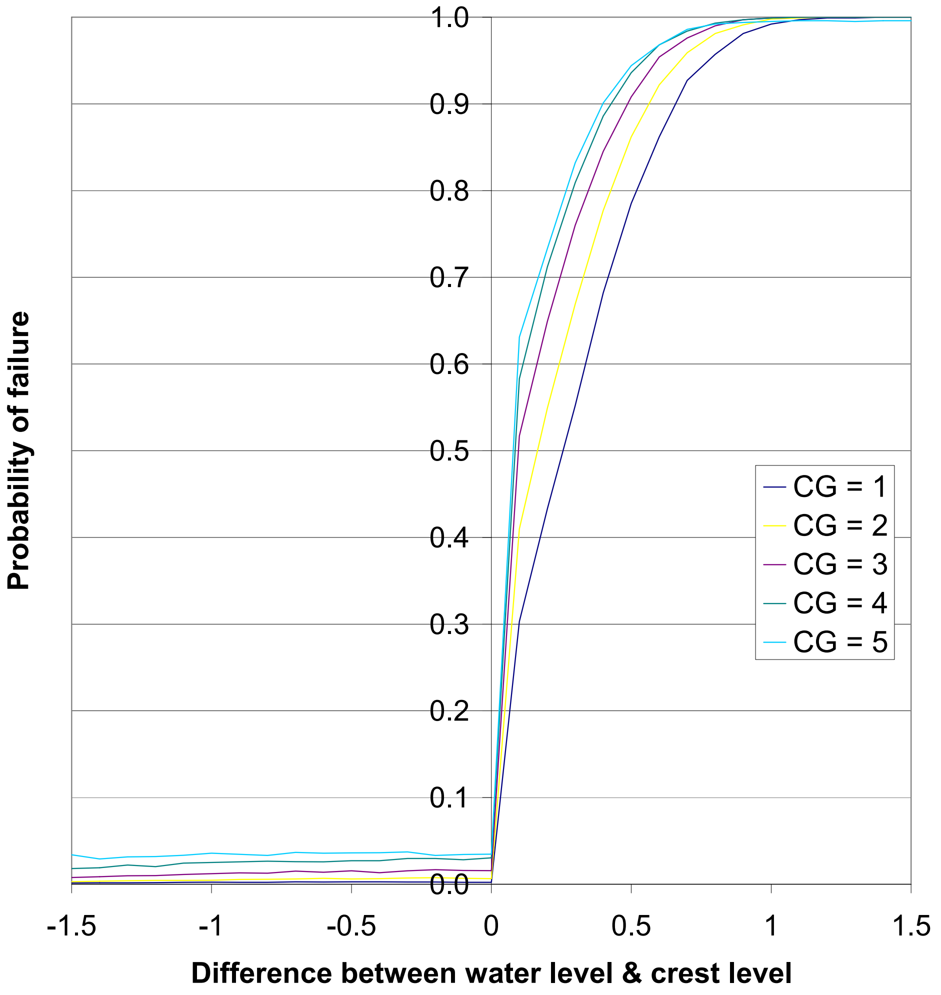

Class 4 - Upper & Lower bounds
Probability of failure
Difference between water level & crest level
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
-2.5
-1.5
-0.5
0.5
1.5
2.5
CG = 1
CG = 2
CG = 3
CG = 4
CG = 5
CG = 1 - Upper
CG = 2 - Upper
CG = 3 - Upper
CG = 4 - Upper
CG = 5 - Upper
CG = 1 - Lower
CG = 2 - Lower
CG = 3 - Lower
CG = 4 - Lower
CG = 5 - Lower

Class 5 - Best estimate condition grades

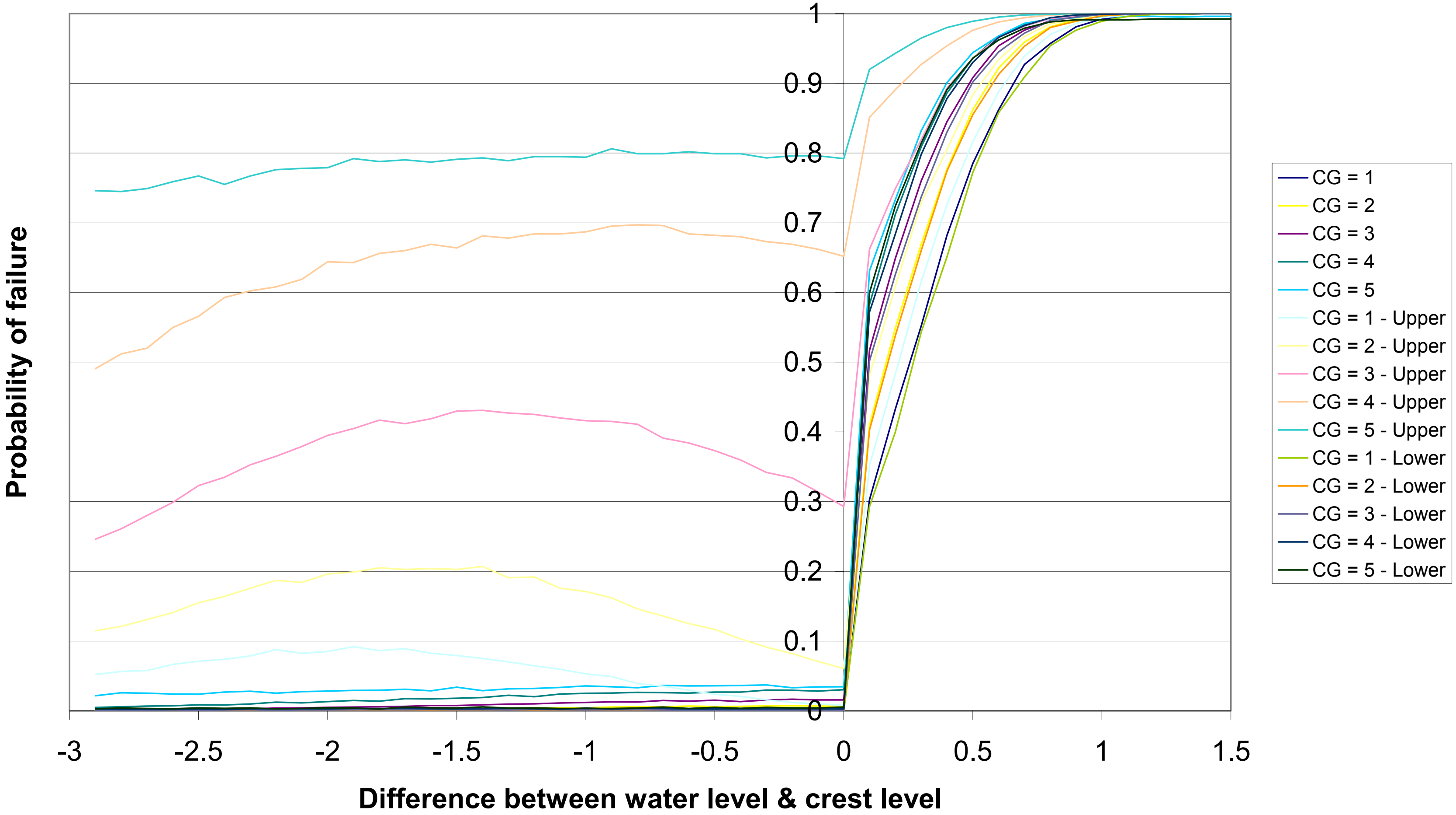



Class 6 - Best estimate condition grades
Probability of failure
Difference between water level & crest level
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
-1.5
-1
-0.5
0
0.5
1
1.5
2
CG = 1
CG = 2
CG = 3
CG = 4
CG = 5

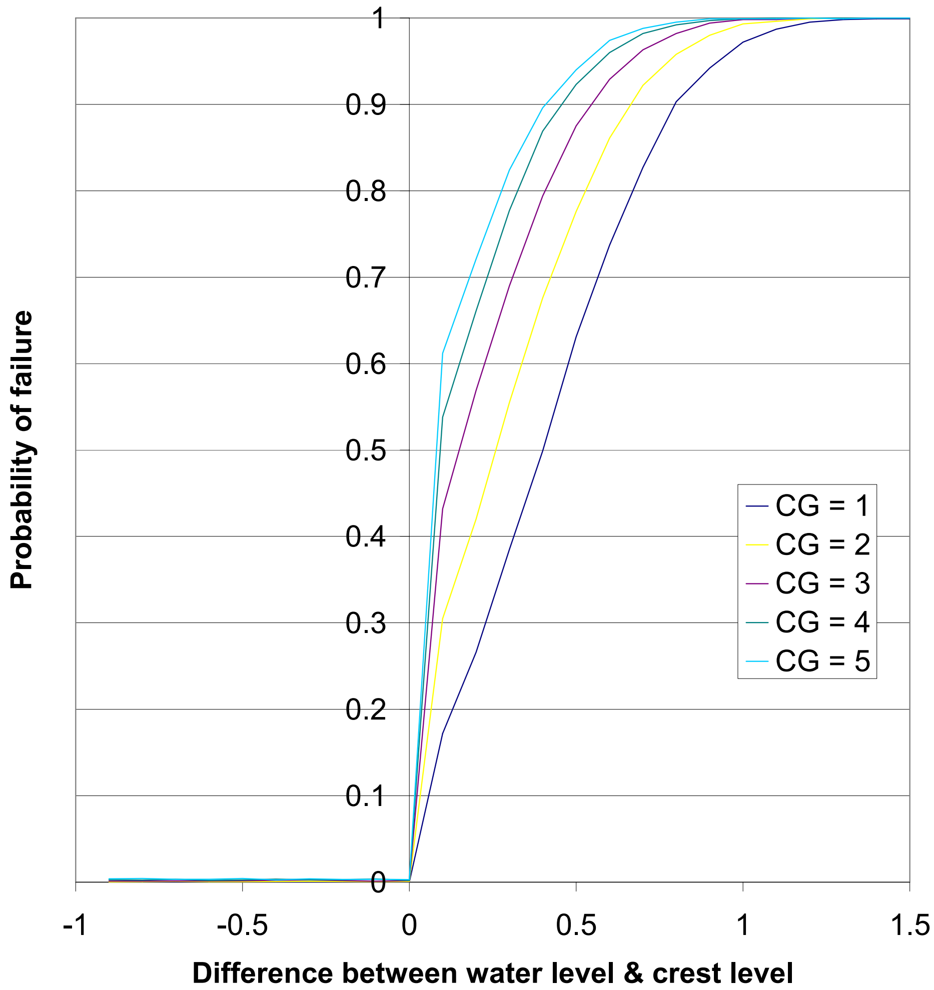
Class 7 - Best estimate condition grades



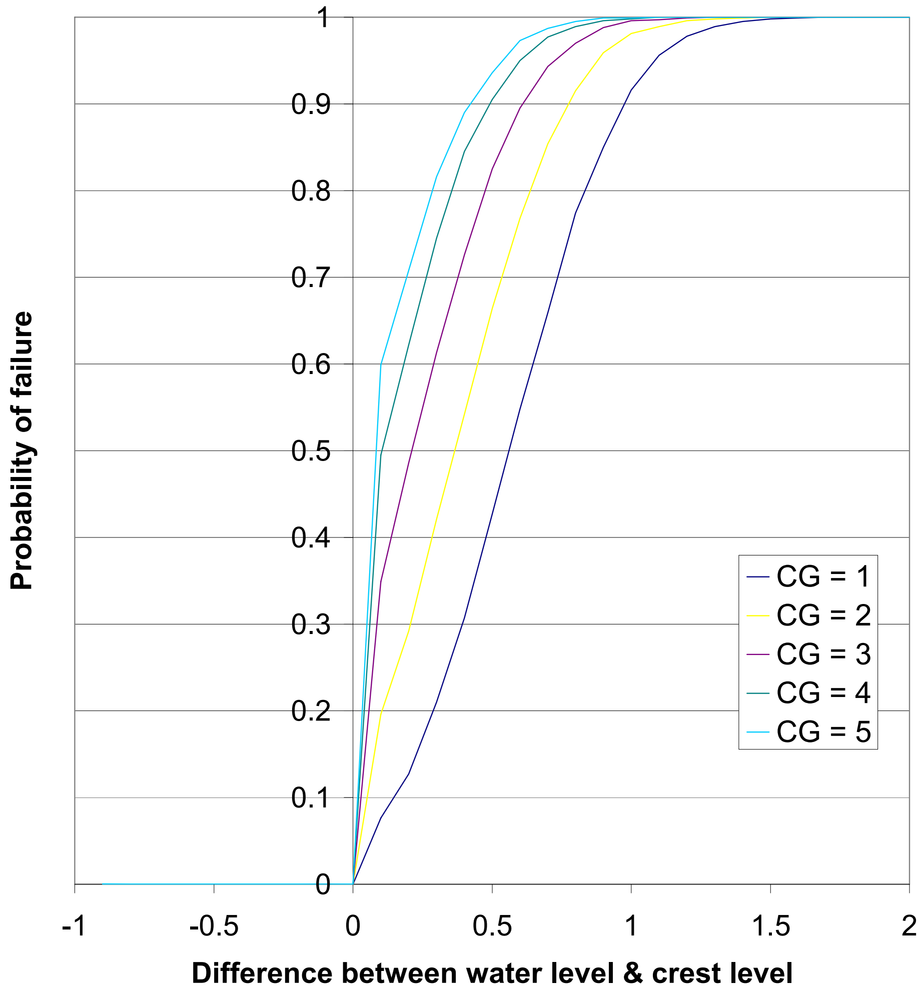
Class 7 - Upper & Lower bounds

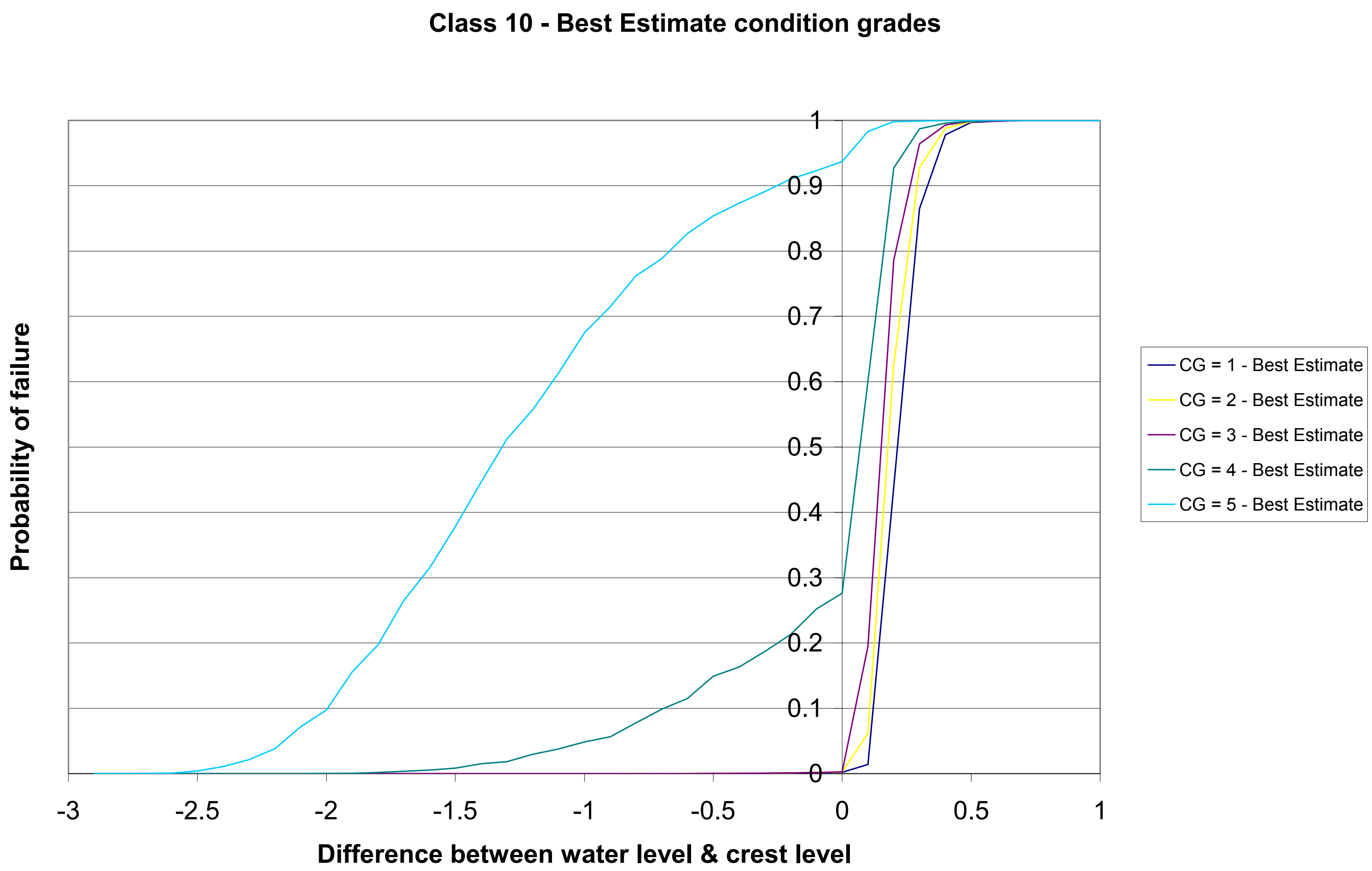


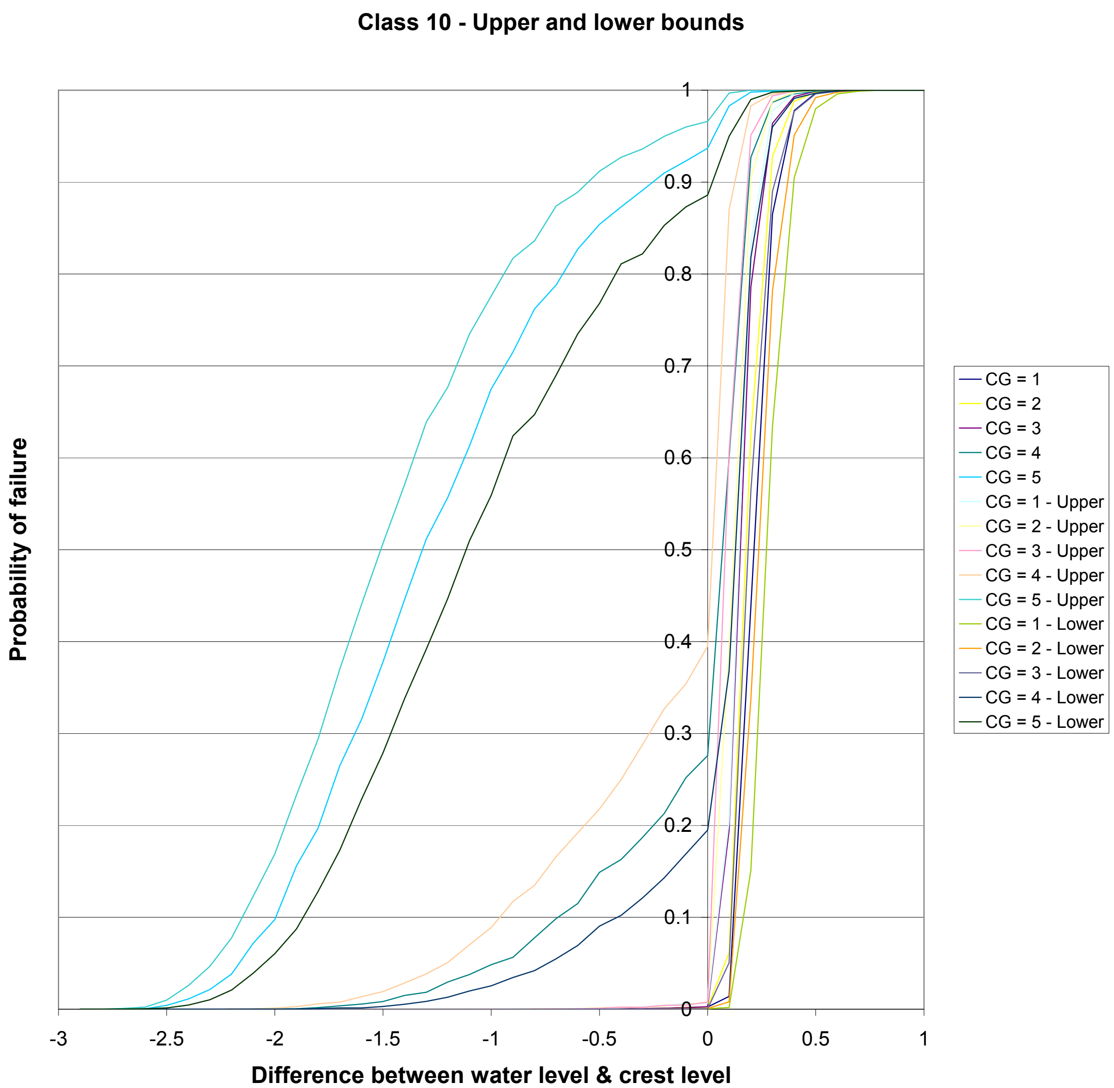
Class 8 - Best estimate condition grades

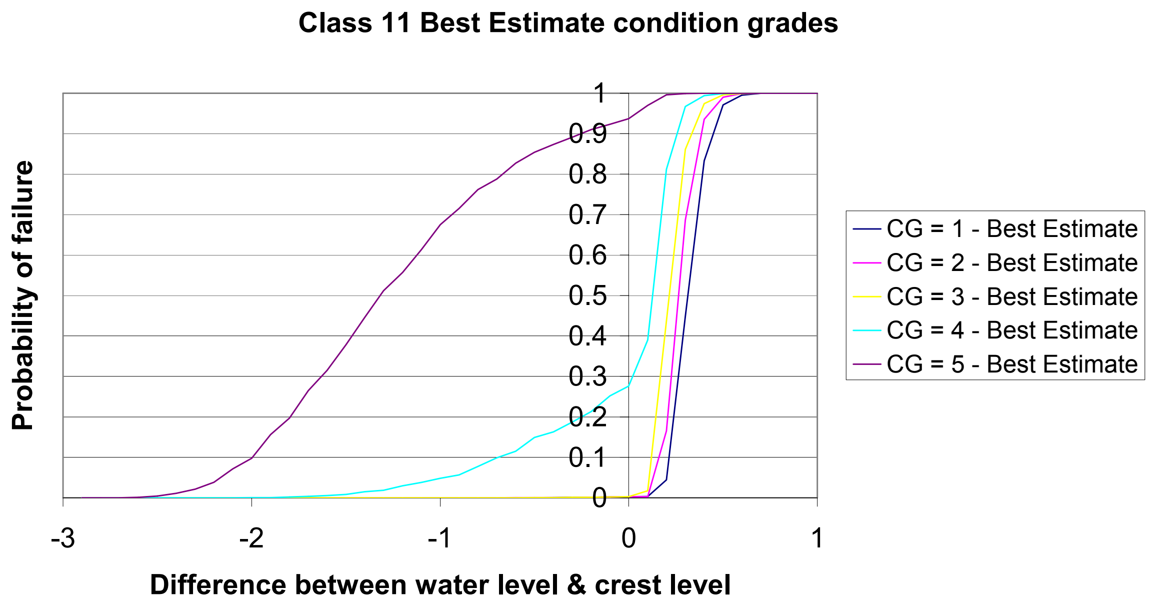


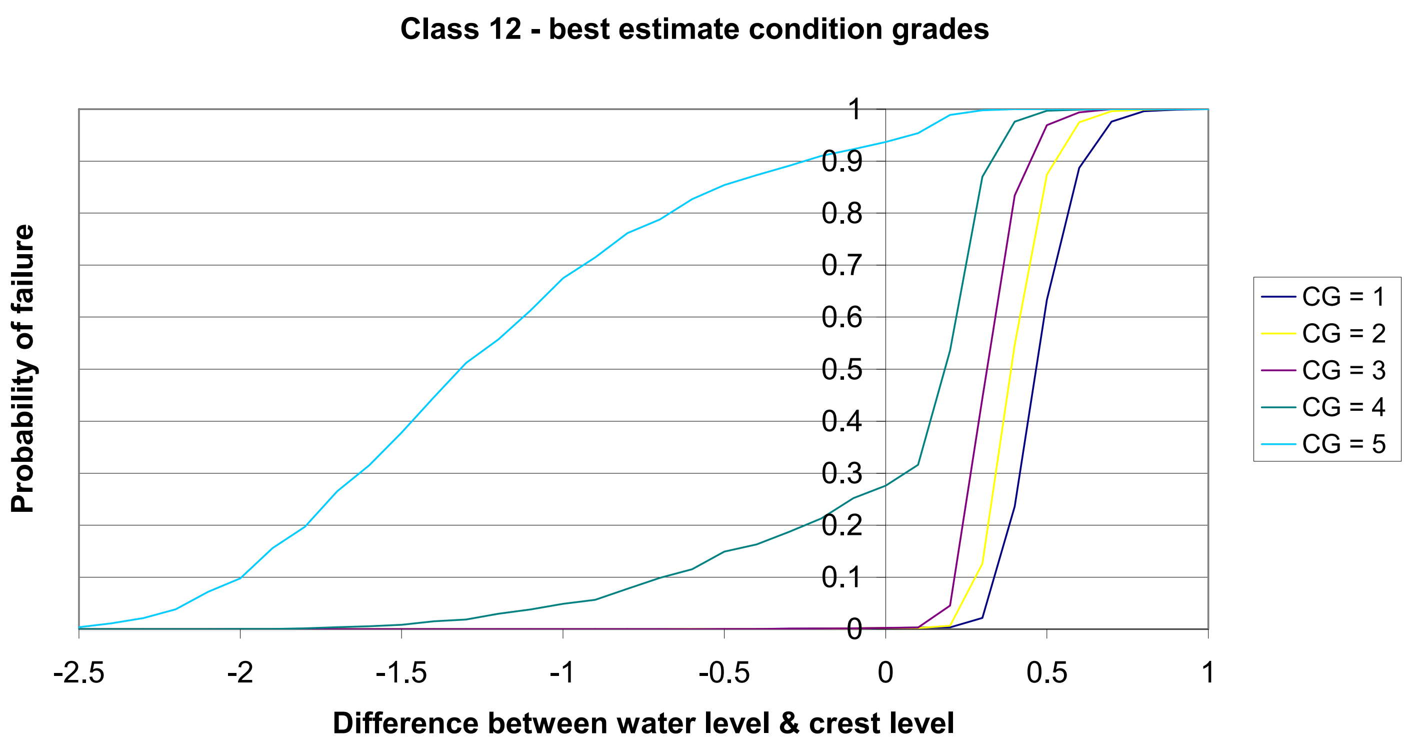
Class 9 - Best estimate condition grades

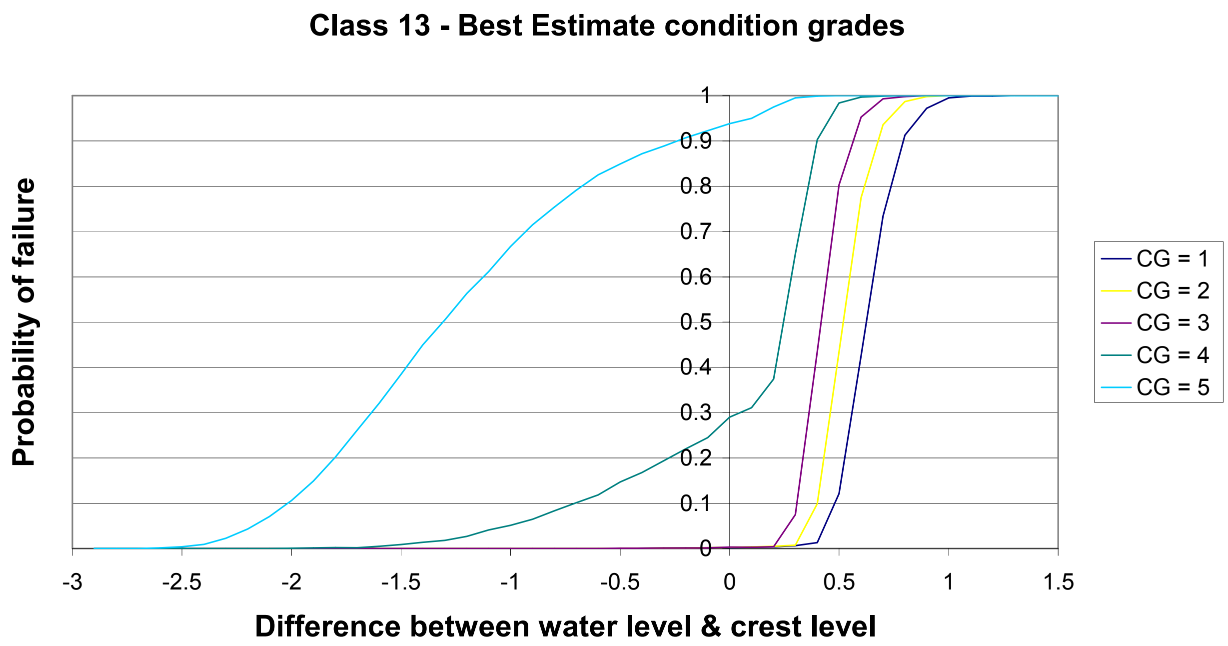


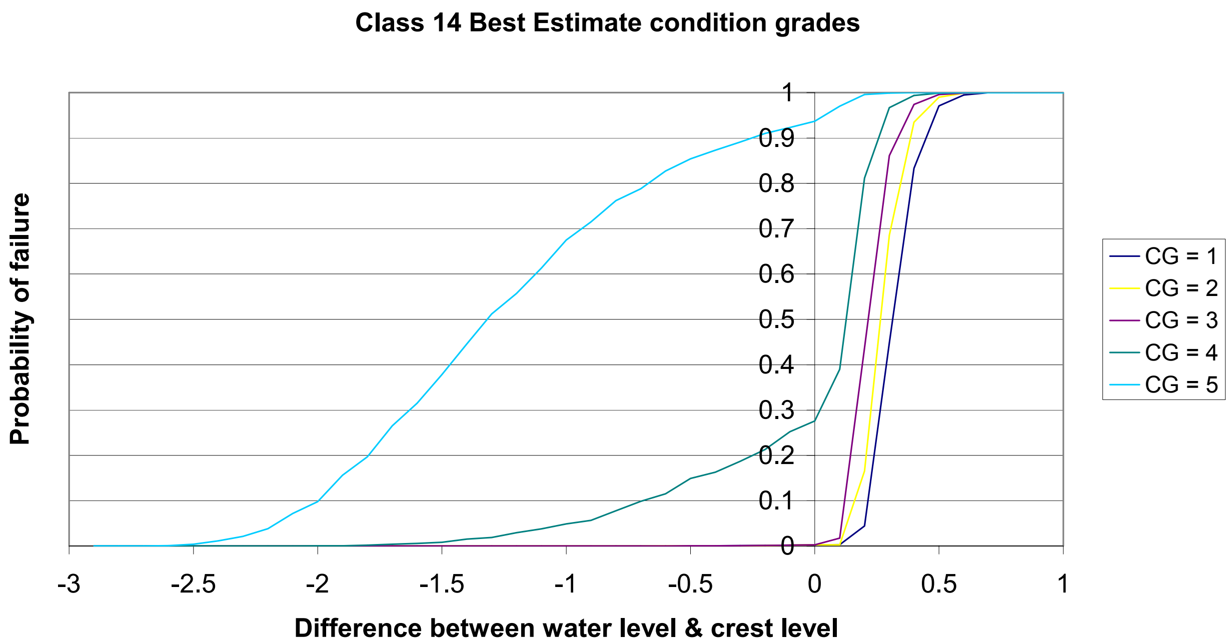

Class 10 - Best Estimate condition grades
Probability of failure
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
-3
-2.5
-2
-1.5
-1
-0.5
0
0.5
1
Difference between water level & crest level
CG = 1 - Best Estimate
CG = 2 - Best Estimate
CG = 3 - Best Estimate
CG = 4 - Best Estimate
CG = 5 - Best Estimate

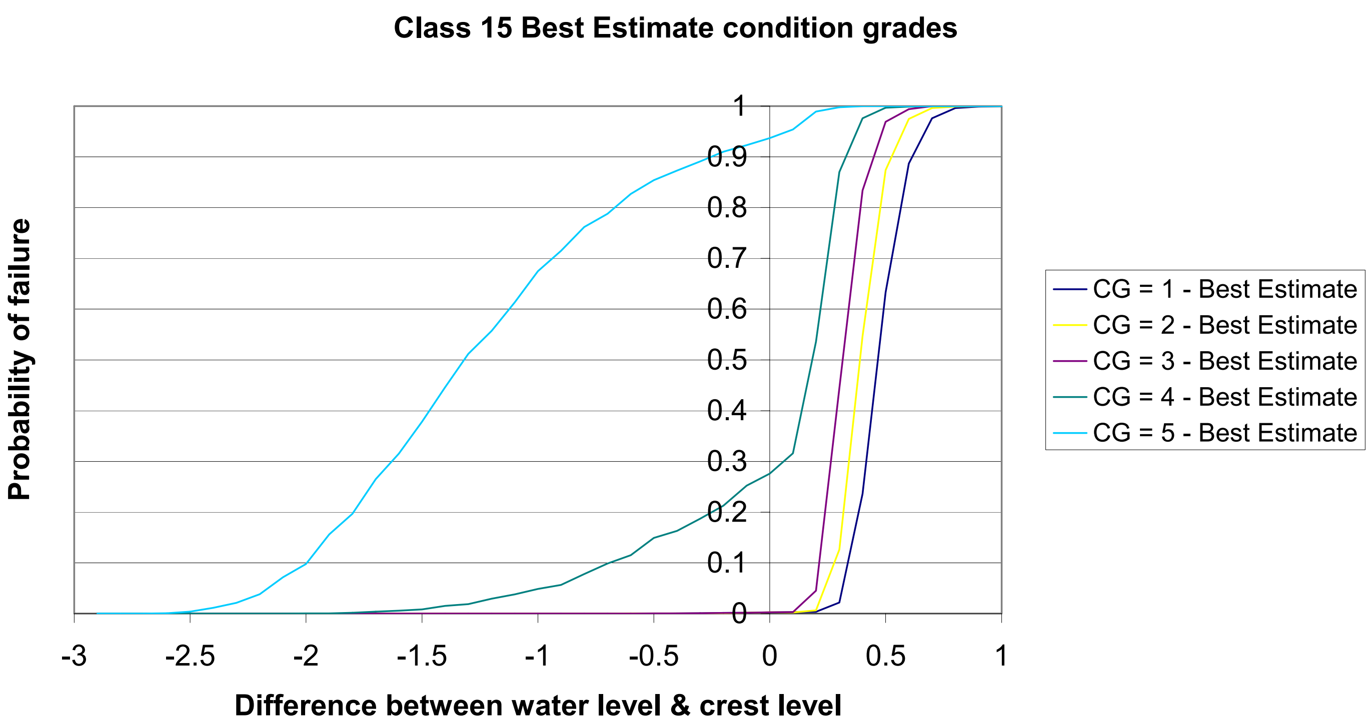

Class 10 - Upper and lower bounds
Probability of failure
Difference between water level & crest level
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
-3
-2.5
-2
-1.5
-1
-0.5
0
0.5
1
CG = 1
CG = 2
CG = 3
CG = 4
CG = 5
CG = 1 - Upper
CG = 2 - Upper
CG = 3 - Upper
CG = 4 - Upper
CG = 5 - Upper
CG = 1 - Lower
CG = 2 - Lower
CG = 3 - Lower
CG = 4 - Lower
CG = 5 - Lower


Class 11 Best Estimate condition grades
Probability of failure
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
-3
-2
-1
0
1
Difference between water level & crest level
CG = 1 - Best Estimate
CG = 2 - Best Estimate
CG = 3 - Best Estimate
CG = 4 - Best Estimate
CG = 5 - Best Estimate

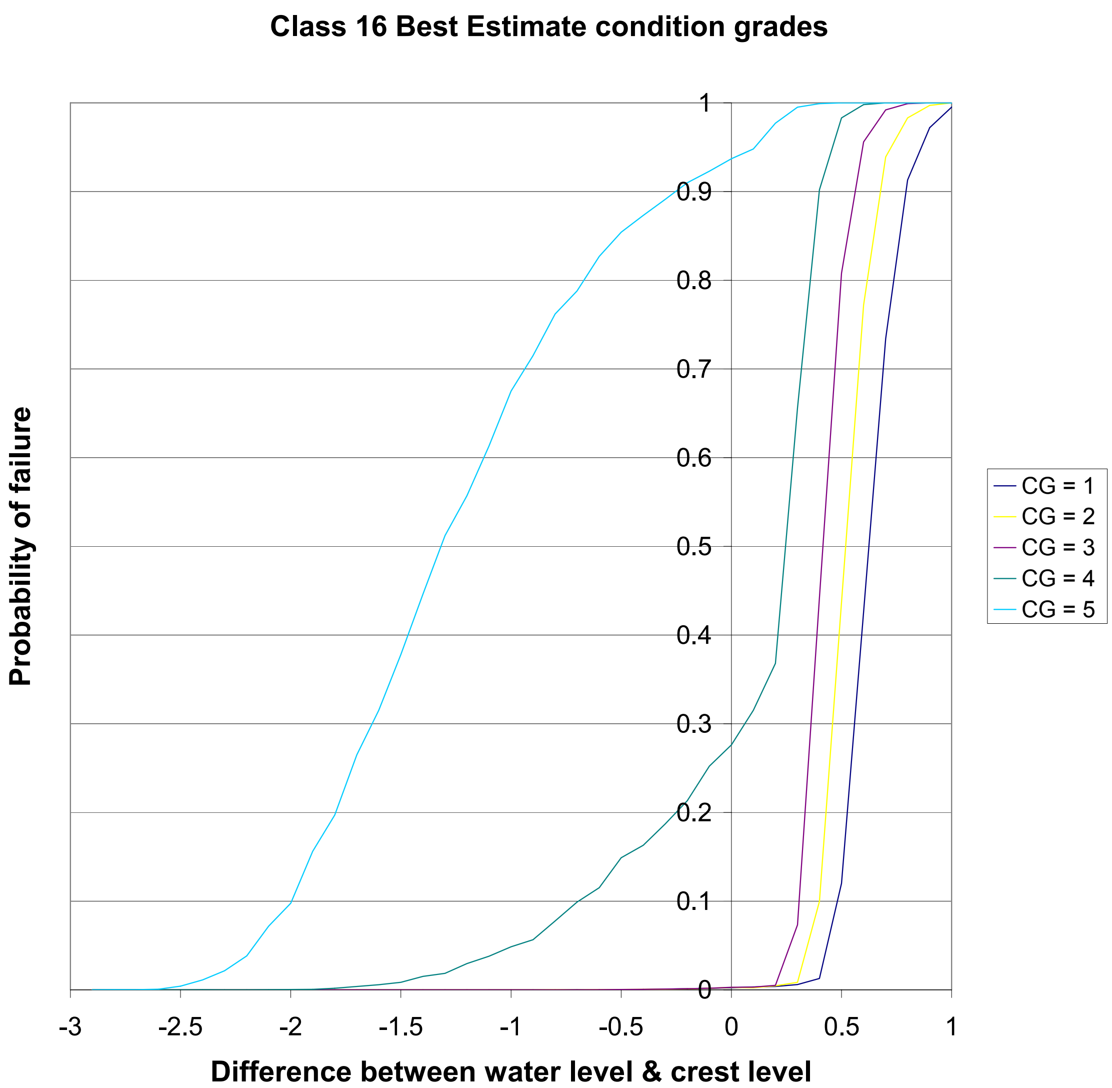

Class 12 - best estimate condition grades
Probability of failure
Difference between water level & crest level
CG = 1
CG = 2
CG = 3
CG = 4
CG = 5
-2.5
-2
-1.5
-1
-0.5
0
0.5
1
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9


Class 13 - Best Estimate condition grades
Probability of failure
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
-3
-2.5
-2
-1.5
-1
-0.5
0
0.5
1
1.5
Difference between water level & crest level
CG = 1
CG = 2
CG = 3
CG = 4
CG = 5

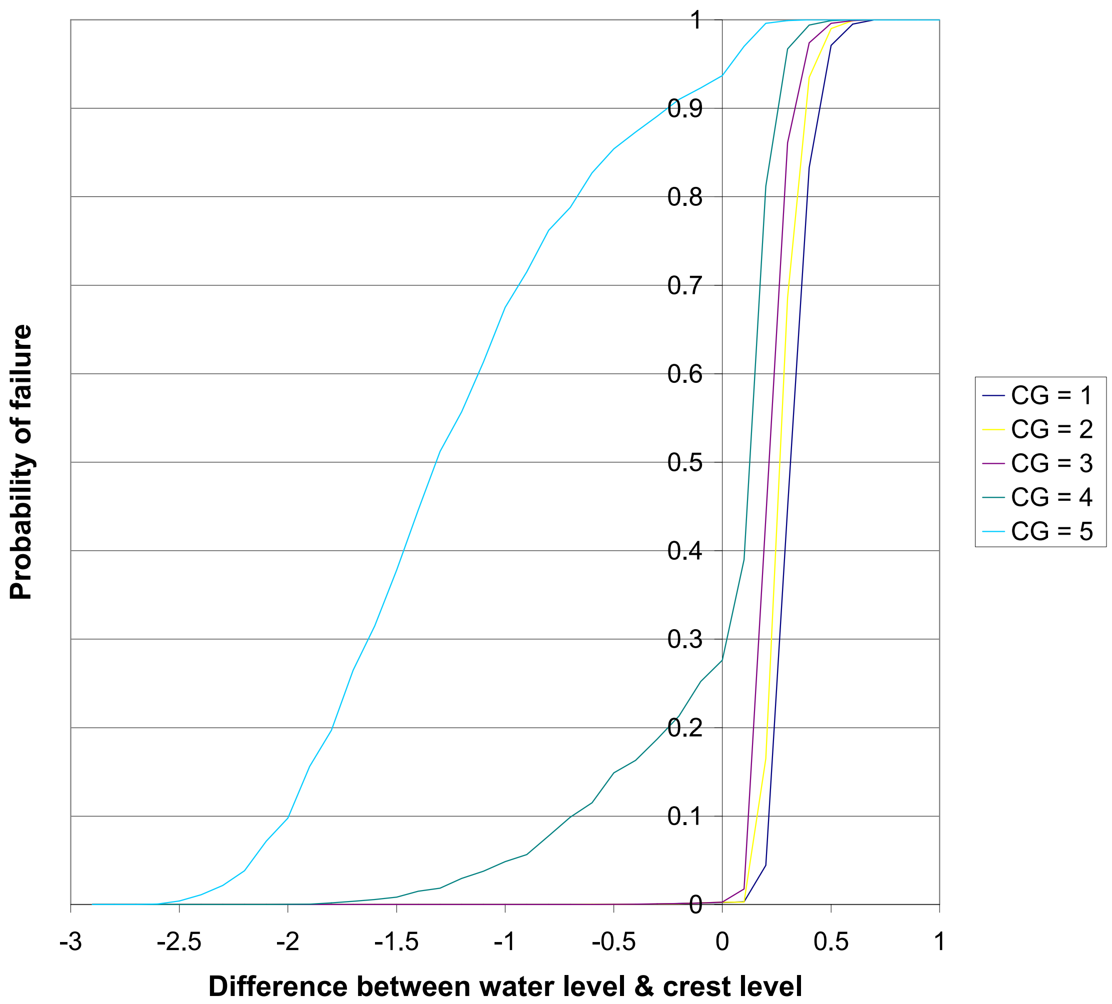

Class 14 Best Estimate condition grades
Probability of failure
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
-3
-2.5
-2
-1.5
-1
-0.5
0
0.5
1
Difference between water level & crest level
CG = 1
CG = 2
CG = 3
CG = 4
CG = 5



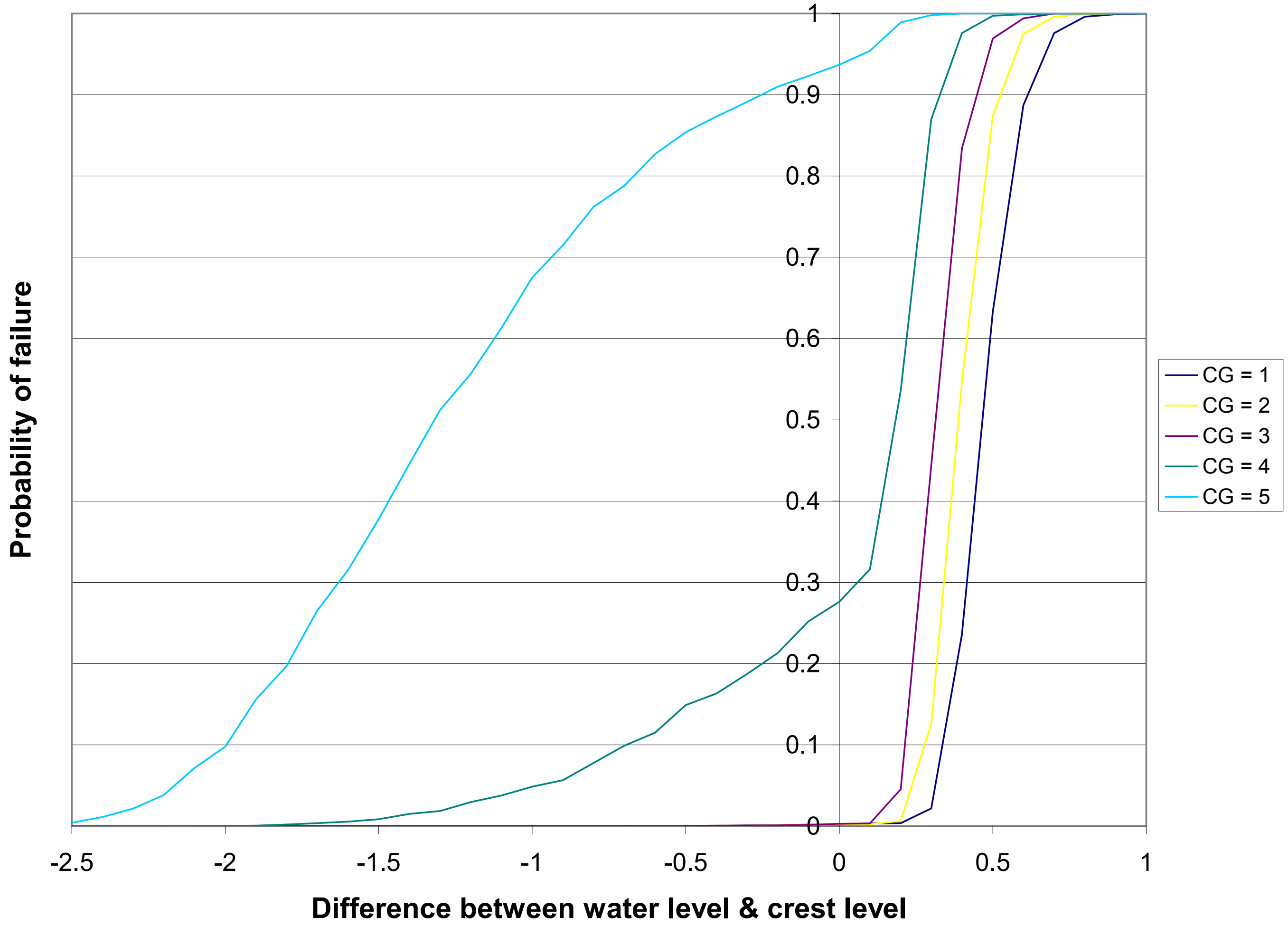
Class 15 Best Estimate condition grades
Probability of failure
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
-3
-2.5
-2
-1.5
-1
-0.5
0
0.5
1
Difference between water level & crest level
CG = 1 - Best Estimate
CG = 2 - Best Estimate
CG = 3 - Best Estimate
CG = 4 - Best Estimate
CG = 5 - Best Estimate


Class 16 Best Estimate condition grades
Probability of failure
Difference between water level & crest level
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
-3
-2.5
-2
-1.5
-1
-0.5
0
0.5
1
CG = 1
CG = 2
CG = 3
CG = 4
CG = 5

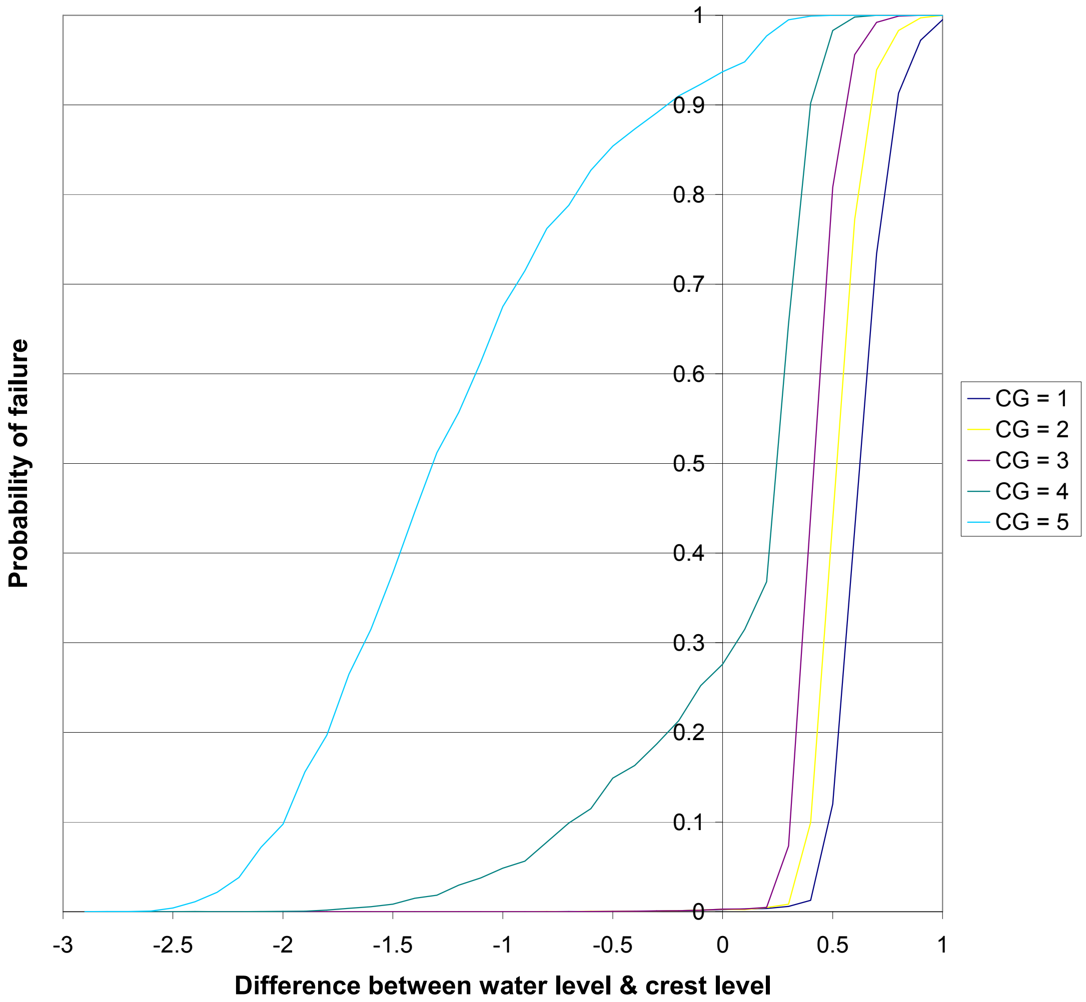
Class 17 Best Estimate condition grades



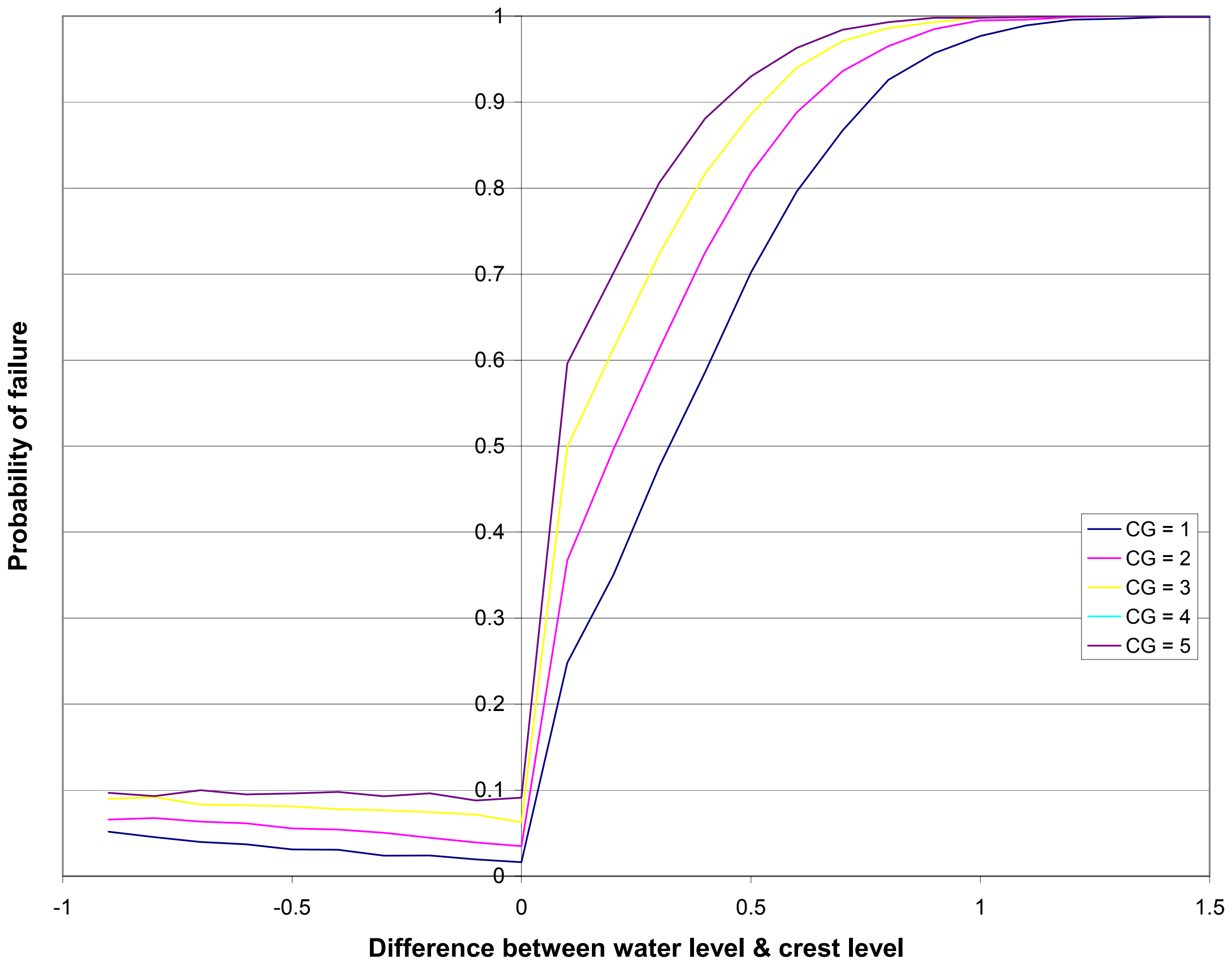
Class 18 Best Estimate condition grades



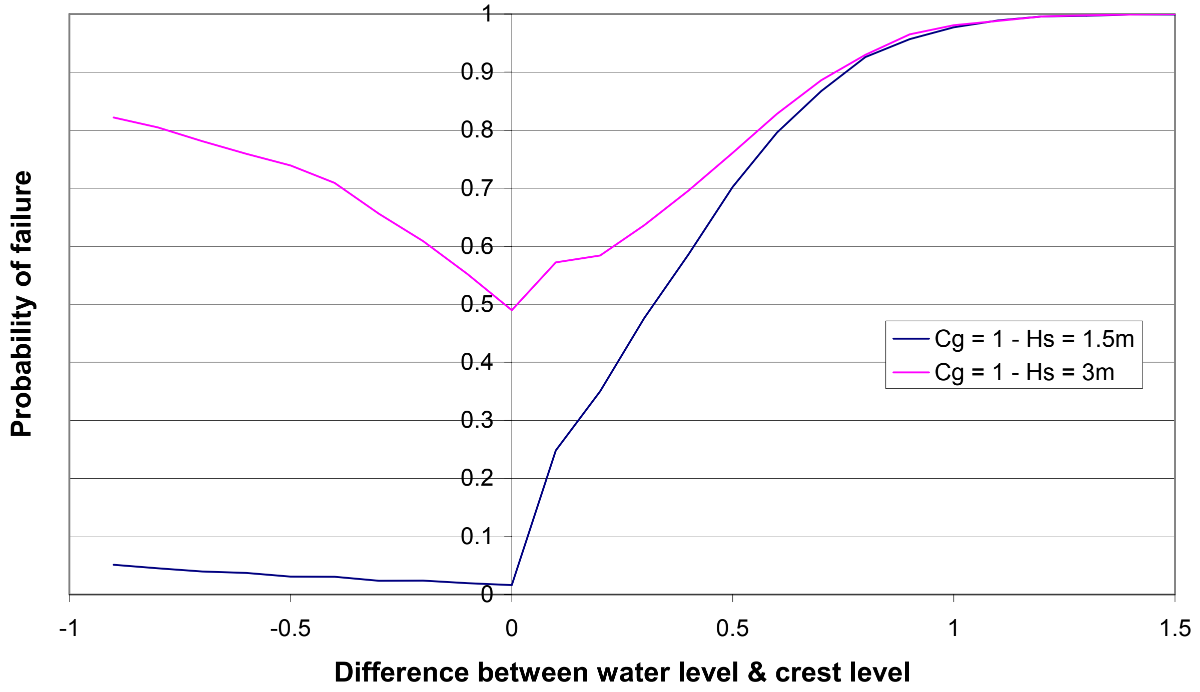
Class 19 Best Estimate condition grades

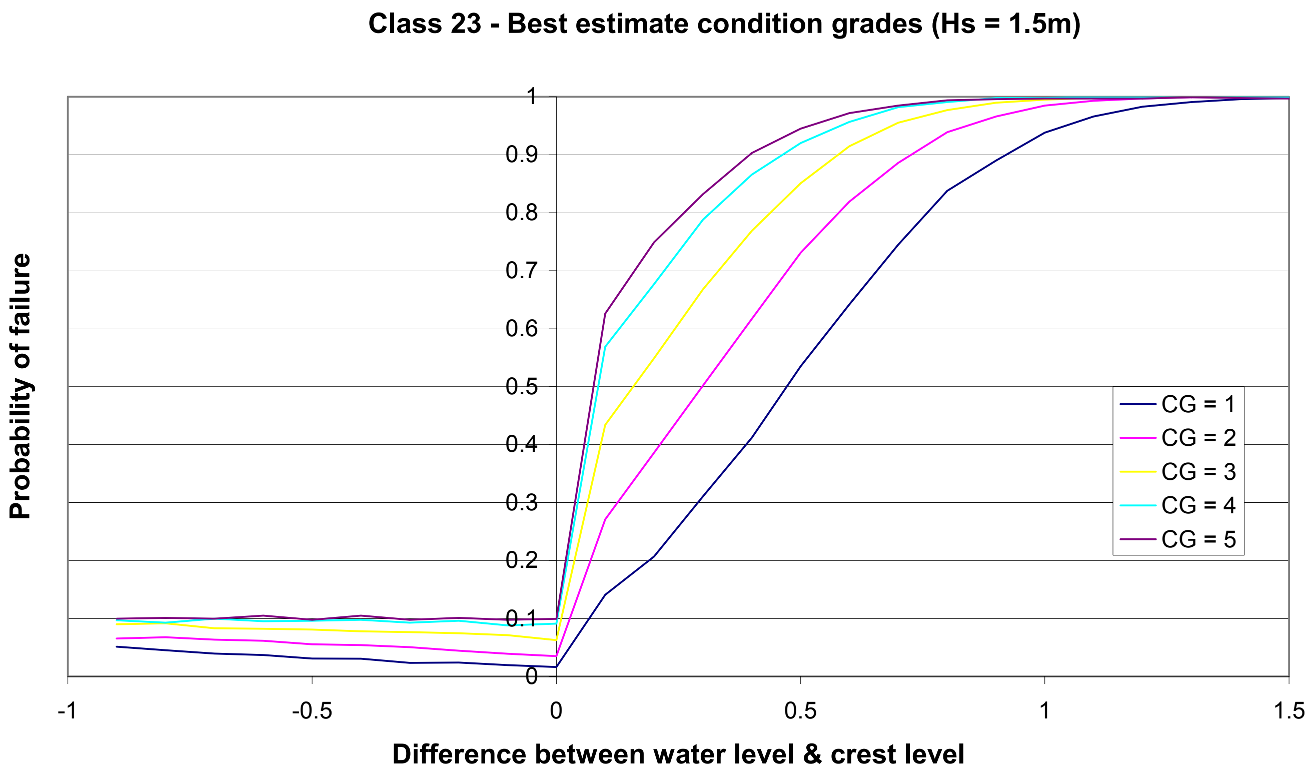


Class 22 - Best estimate condition grades (Hs = 1.5m)

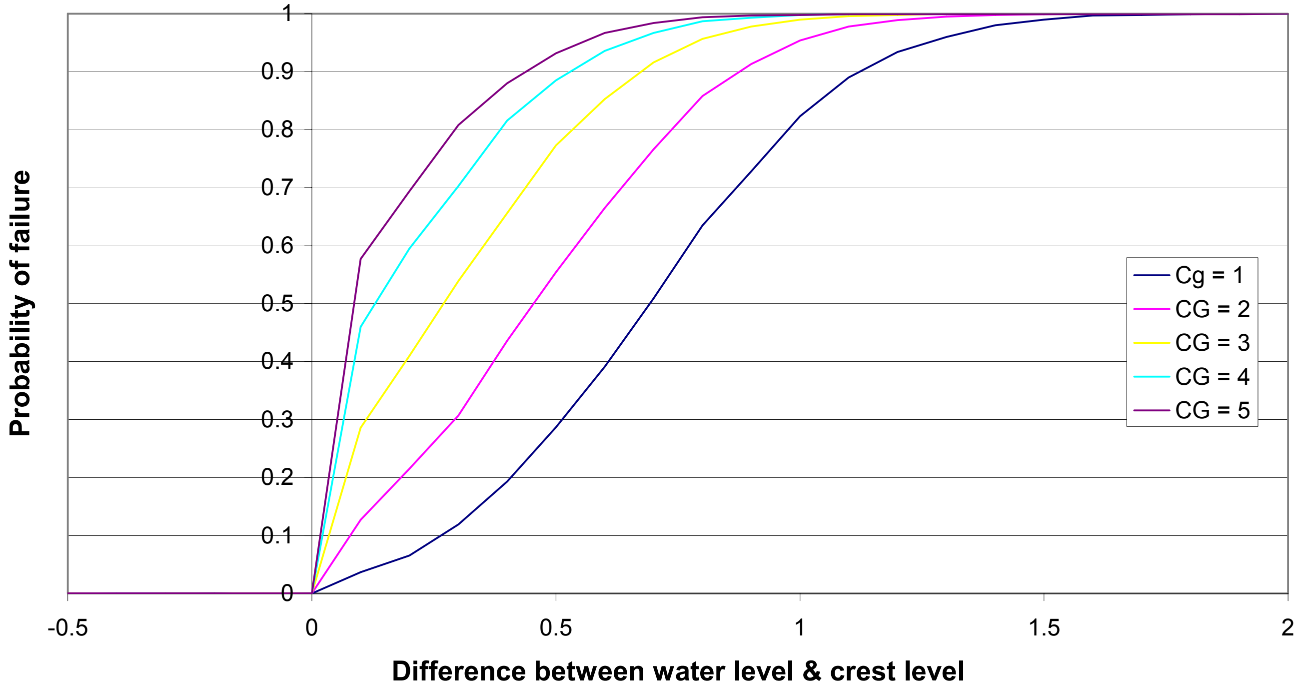


Class 22 - Comparison Hs = 1.5 and Hs = 3m

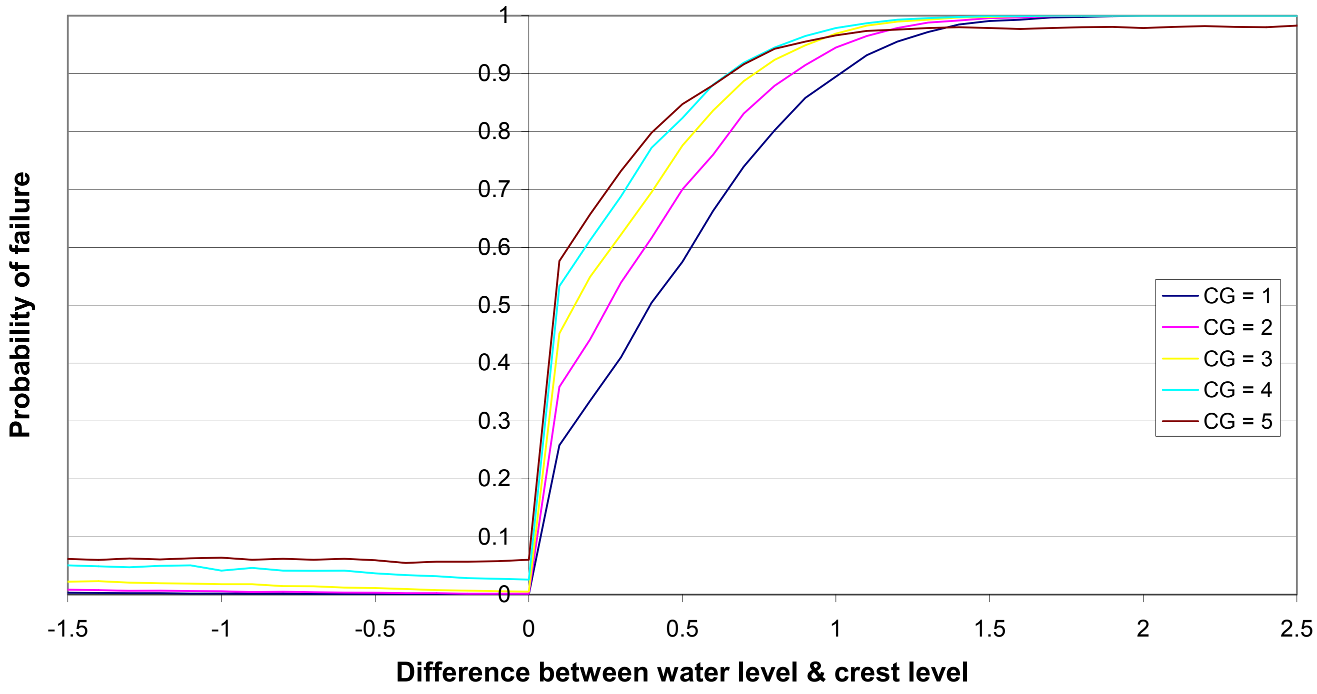



Class 23 - Best estimate condition grades (Hs = 1.5m)
Probability of failure
Difference between water level & crest level
CG = 1
CG = 2
CG = 3
CG = 4
CG = 5
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
-1
-0.5
0
0.5
1
1.5

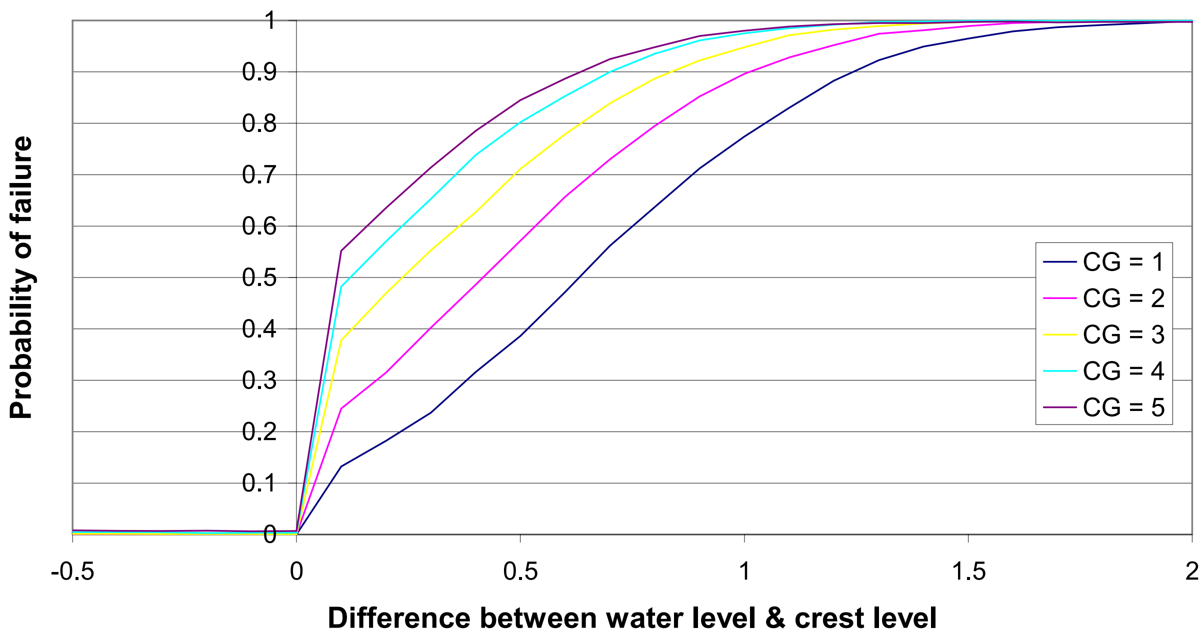
Class 24 - Best estimate condition grades (Hs = 1.5m)



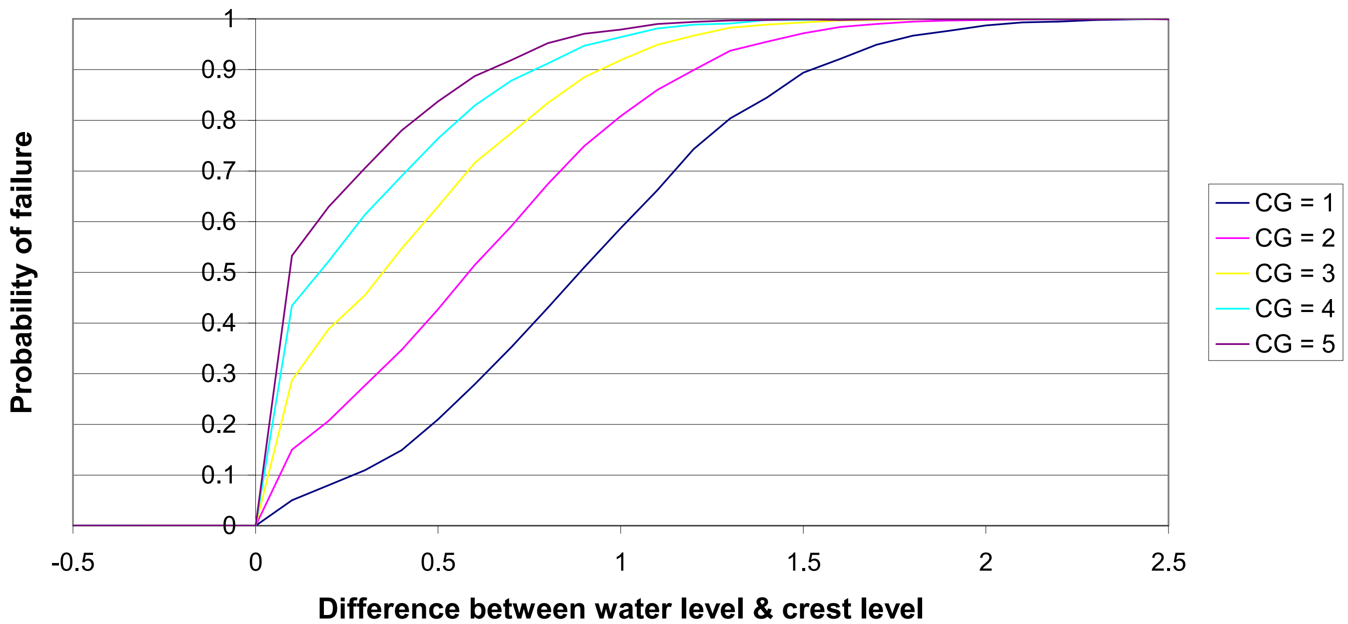
Class 25 - Best estimate condition grades (Hs = 1.5m)

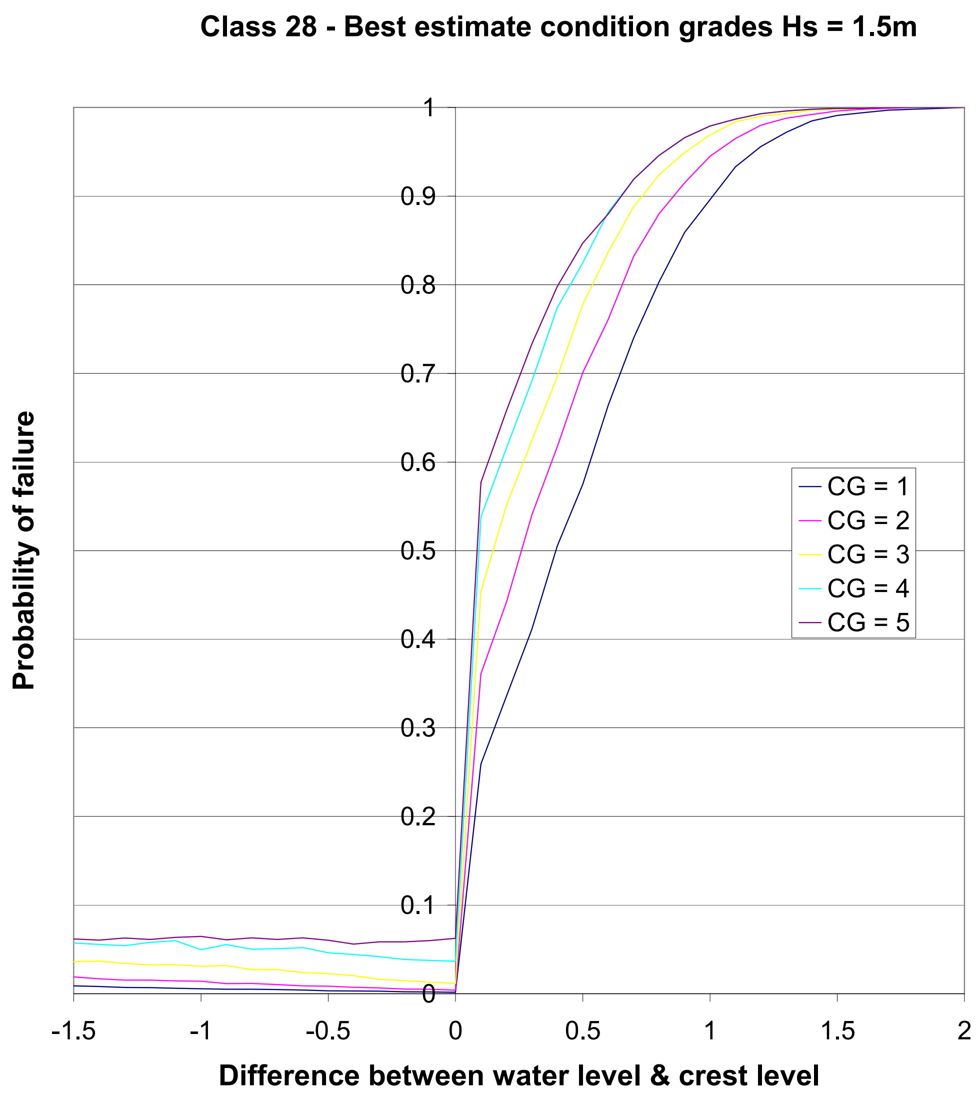


Class 26 - Best estimate condition grades (Hs = 1.5m)



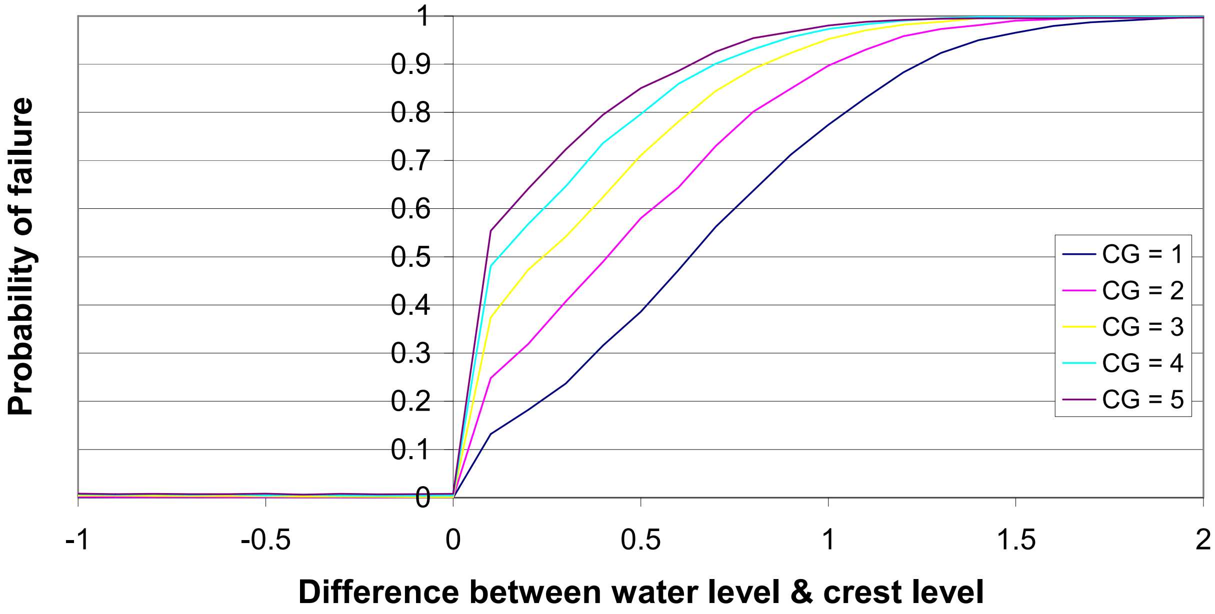
Class 27 - Best estimate condition grades (Hs = 1.5m)

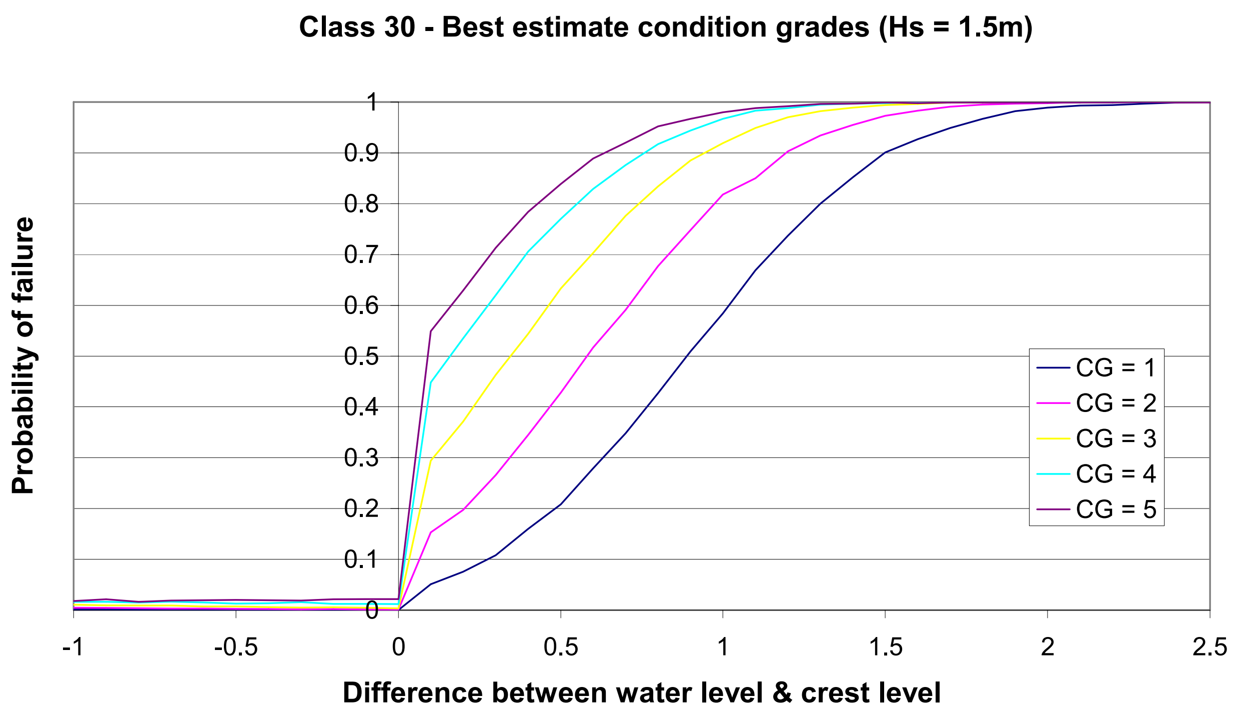




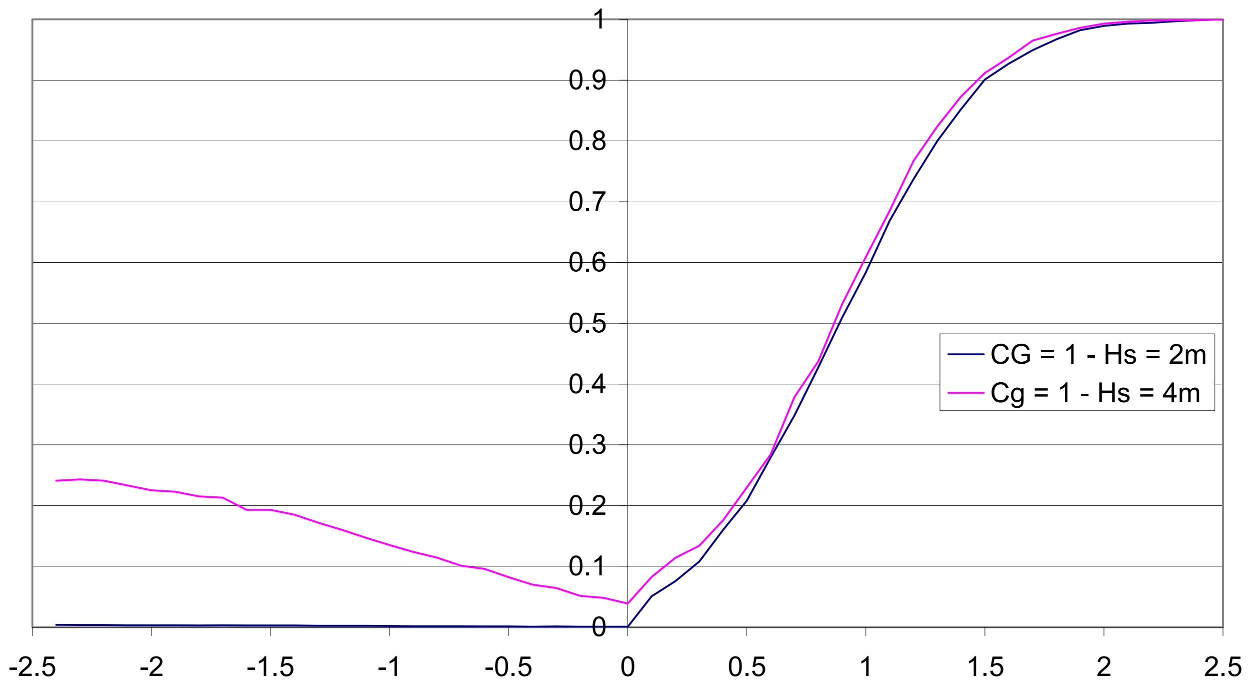
Class 28 - Best estimate condition grades Hs = 1.5m
Probability of failure
Difference between water level & crest level
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
-1.5
-1
-0.5
0
0.5
1
1.5
2
CG = 1
CG = 2
CG = 3
CG = 4
CG = 5

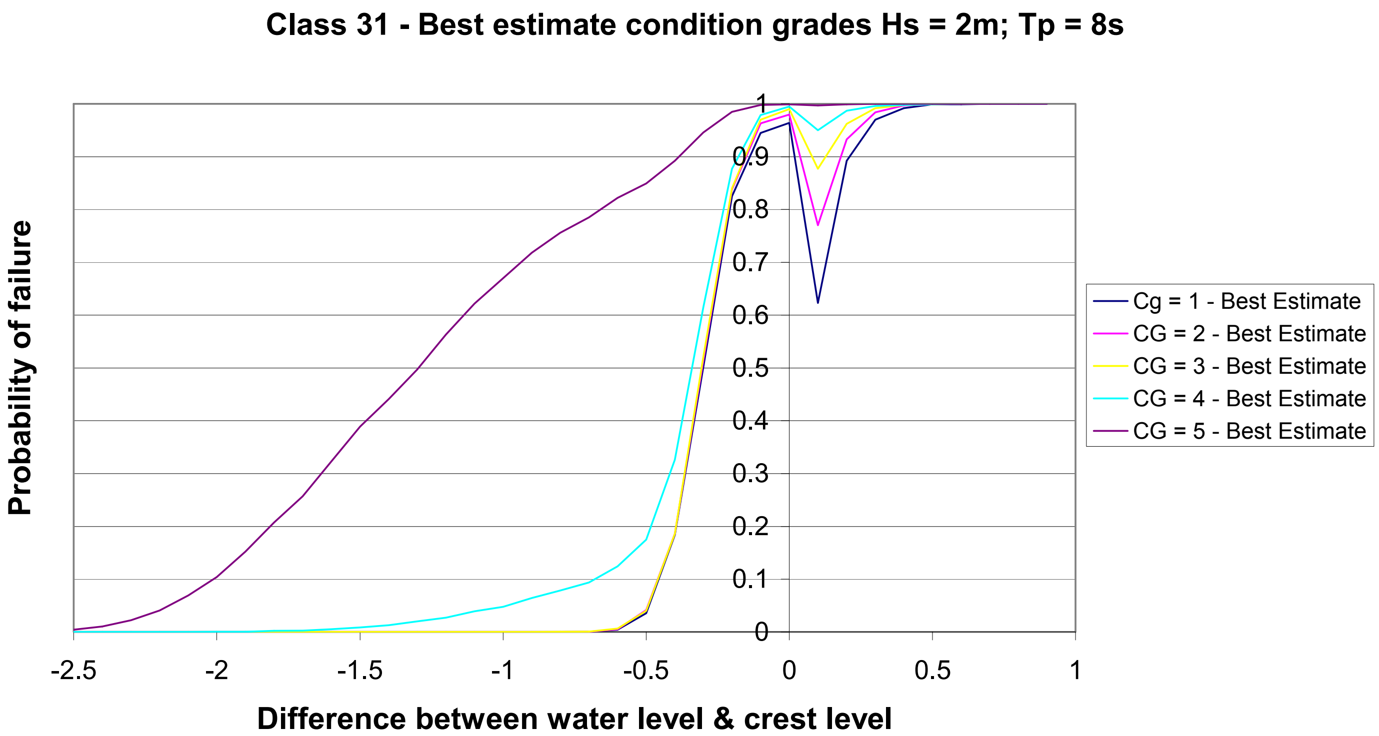
Class 29 - Best estimate condition grades (Hs = 1.5m)

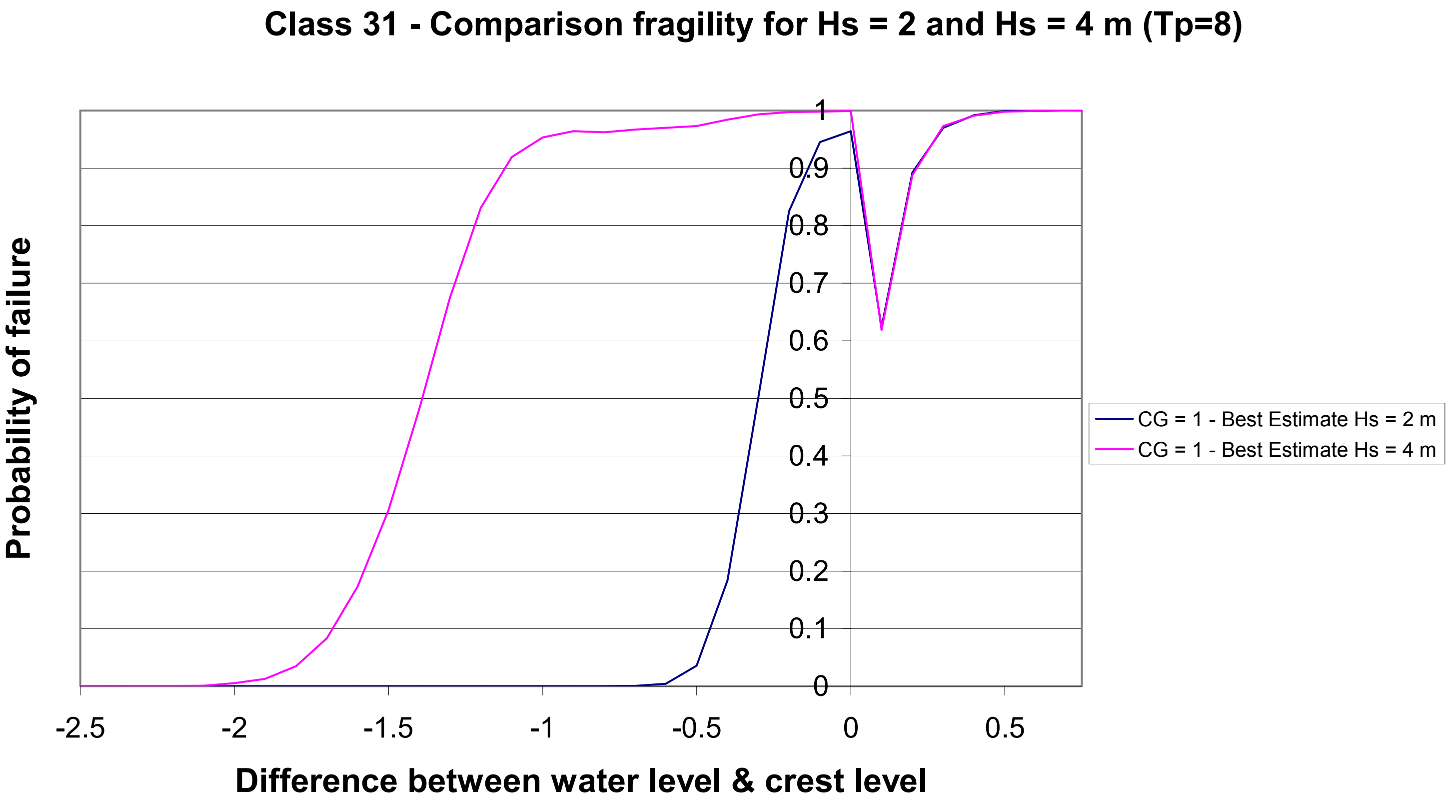



Class 30 - Best estimate condition grades (Hs = 1.5m)
Probability of failure
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
-1
-0.5
0
0.5
1
1.5
2
2.5
Difference between water level & crest level
CG = 1
CG = 2
CG = 3
CG = 4
CG = 5

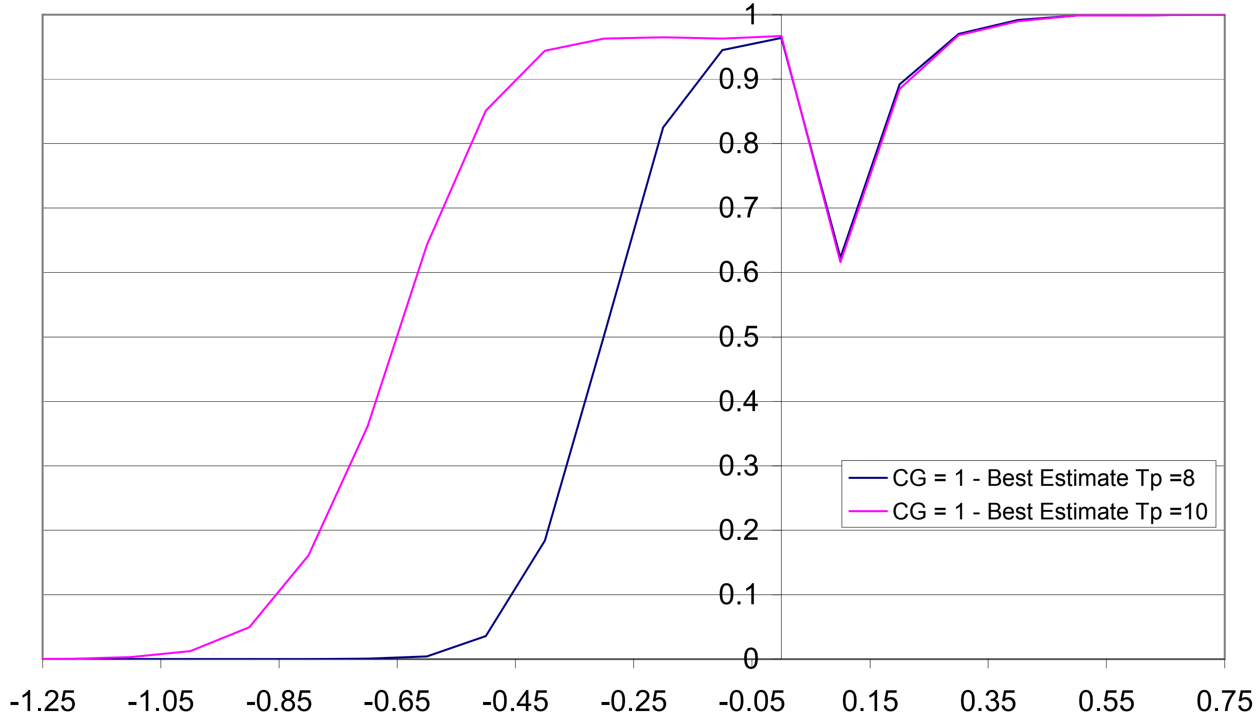
Class 30 - comparison different significant wave heights Hs = 1.5 and Hs = 3 m



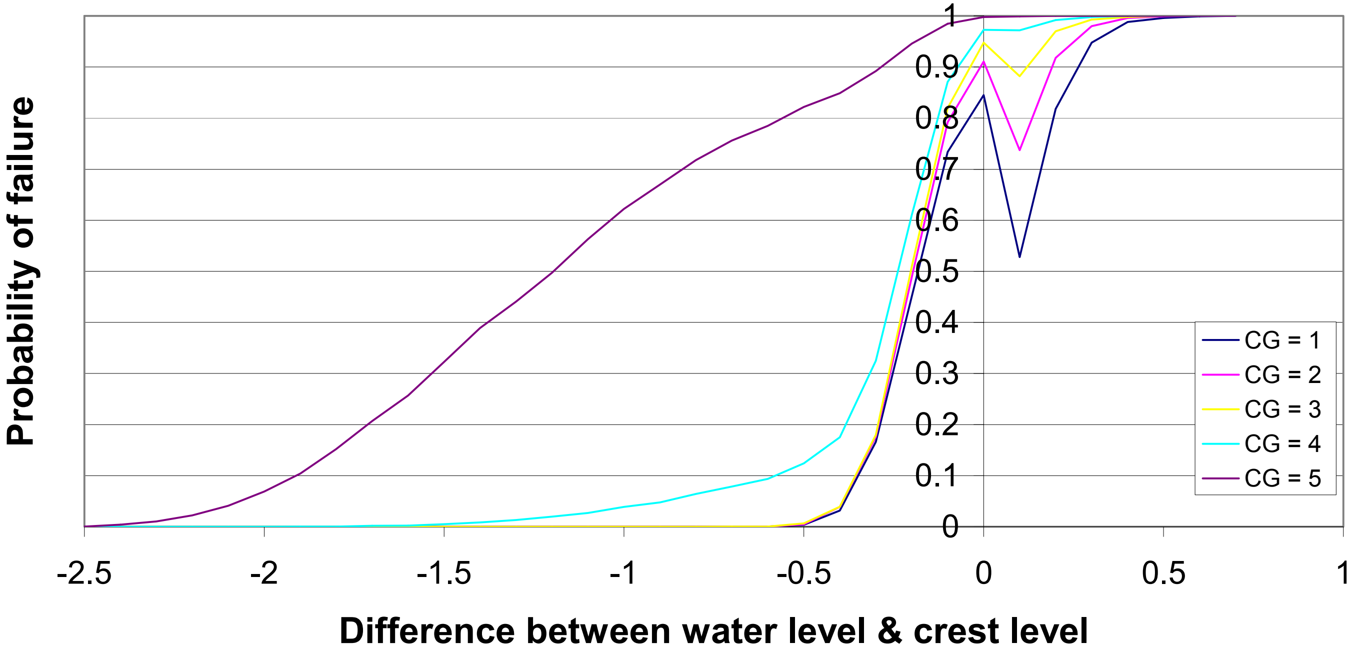

Class 31 - Best estimate condition grades Hs = 2m; Tp = 8s
Probability of failure
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
-2.5
-2
-1.5
-1
-0.5
0
0.5
1
Difference between water level & crest level
Cg = 1 - Best Estimate
CG = 2 - Best Estimate
CG = 3 - Best Estimate
CG = 4 - Best Estimate
CG = 5 - Best Estimate

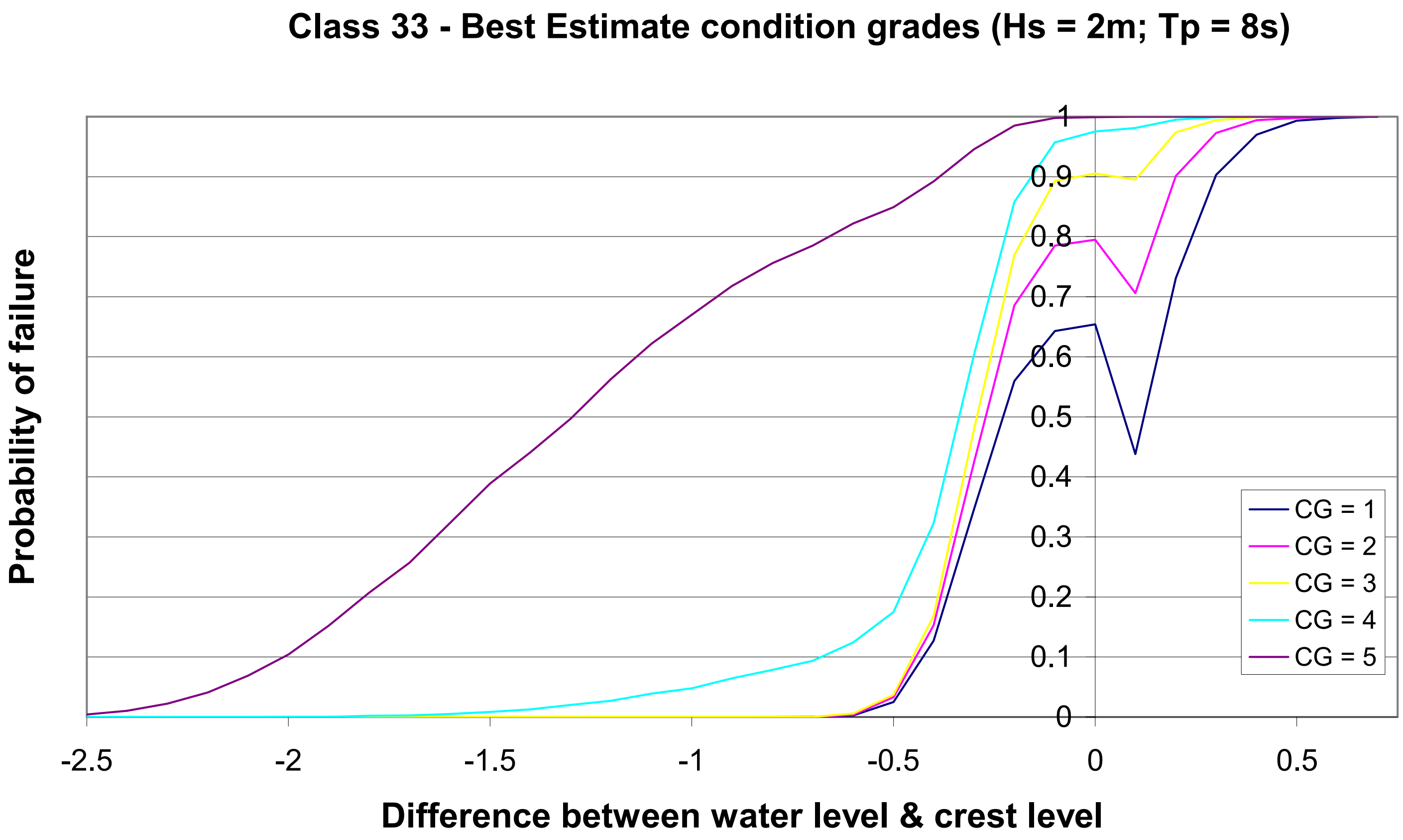

Class 31 - Comparison fragility for Hs = 2 and Hs = 4 m (Tp=8)
Probability of failure
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
-2.5
-2
-1.5
-1
-0.5
0
0.5
Difference between water level & crest level
CG = 1 - Best Estimate Hs = 2 m
CG = 1 - Best Estimate Hs = 4 m

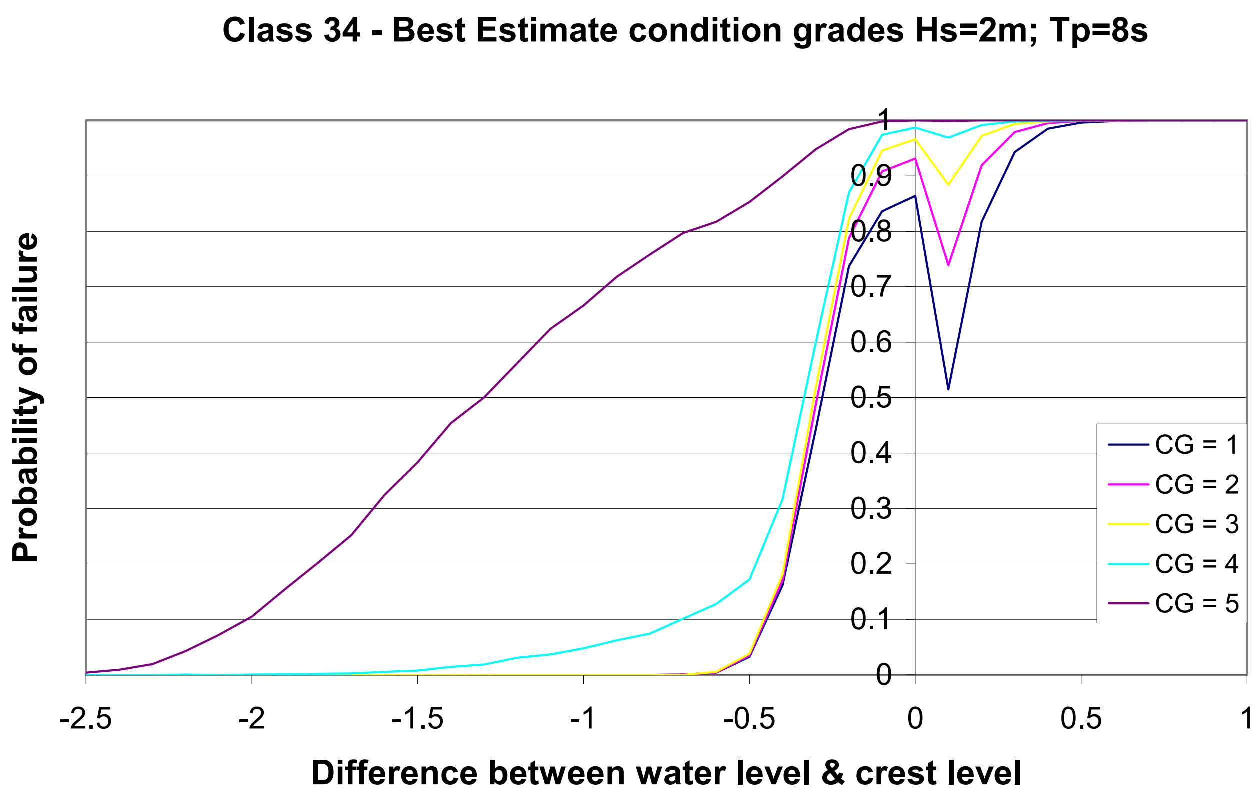
Class 31 - Comparison fragility for Tp=8 and Tp=10 s (Hs = 2)

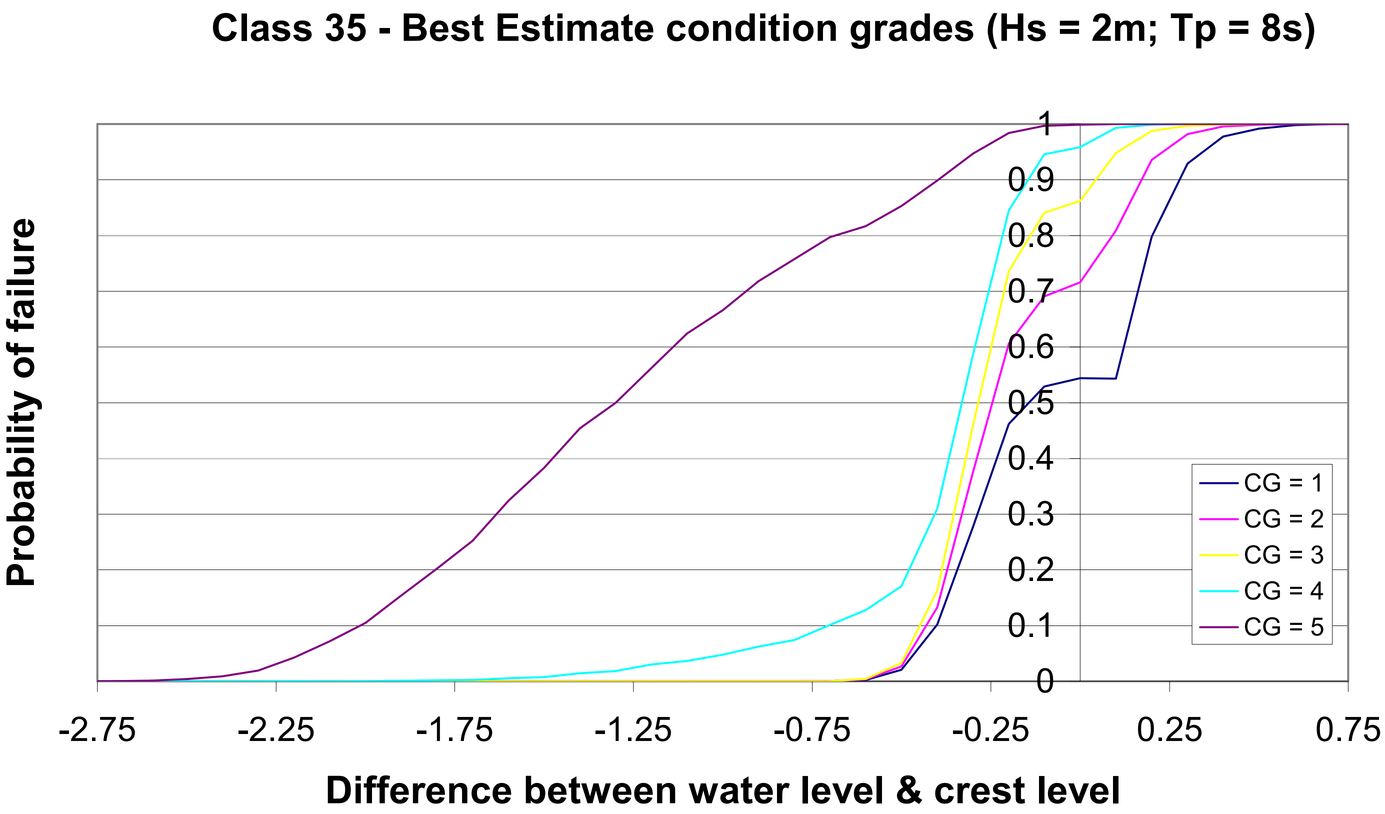


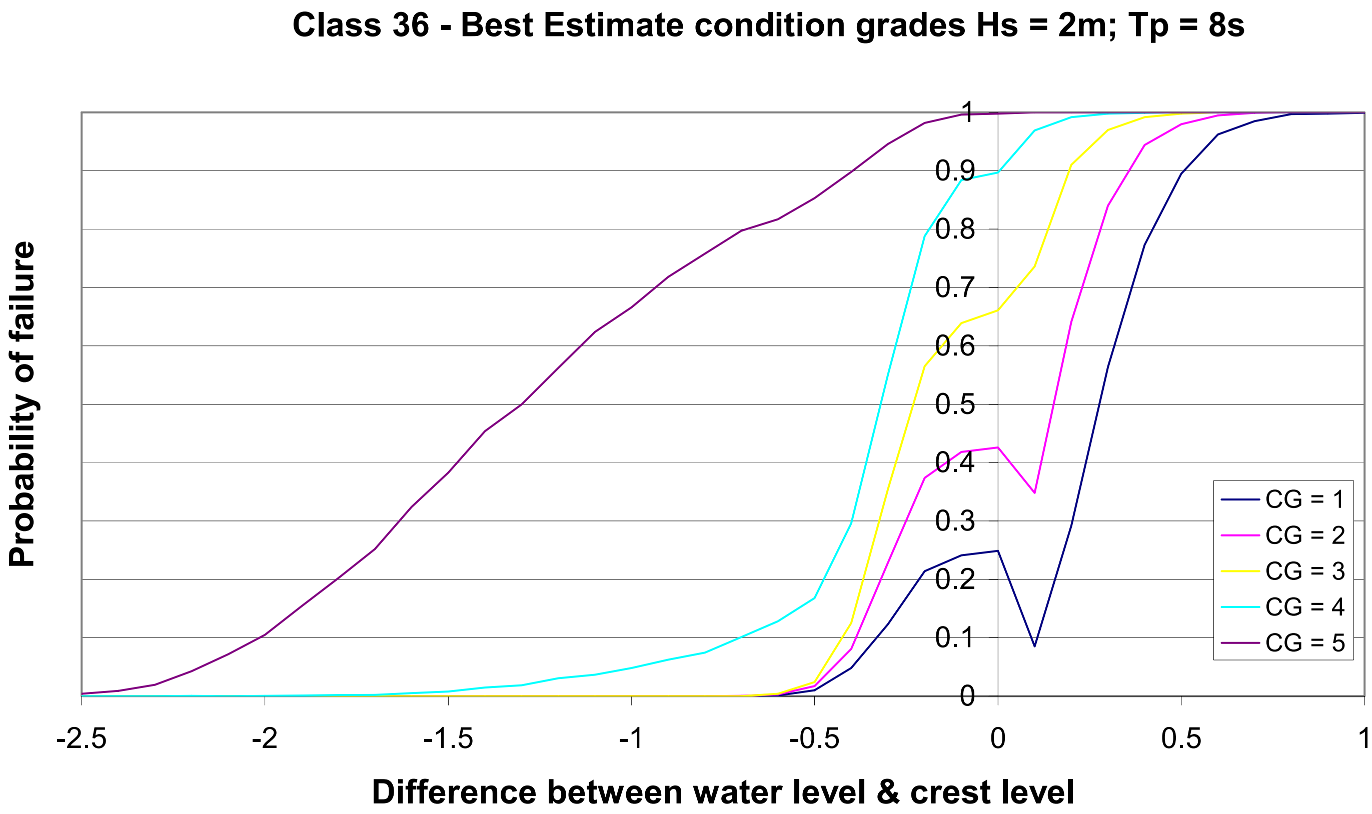
Class 32 - Best estimate condition grades Hs = 2m; Tp=8s

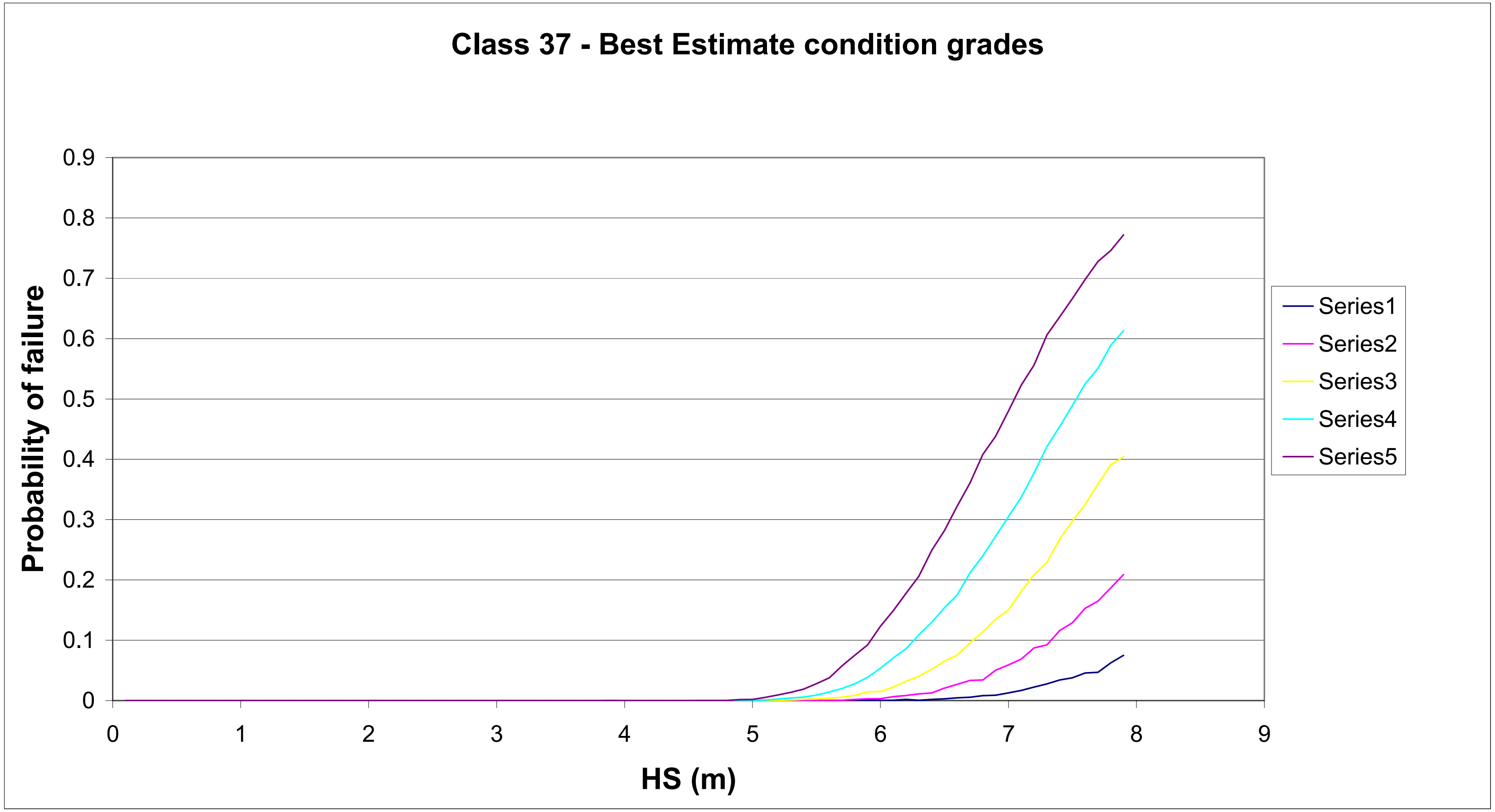


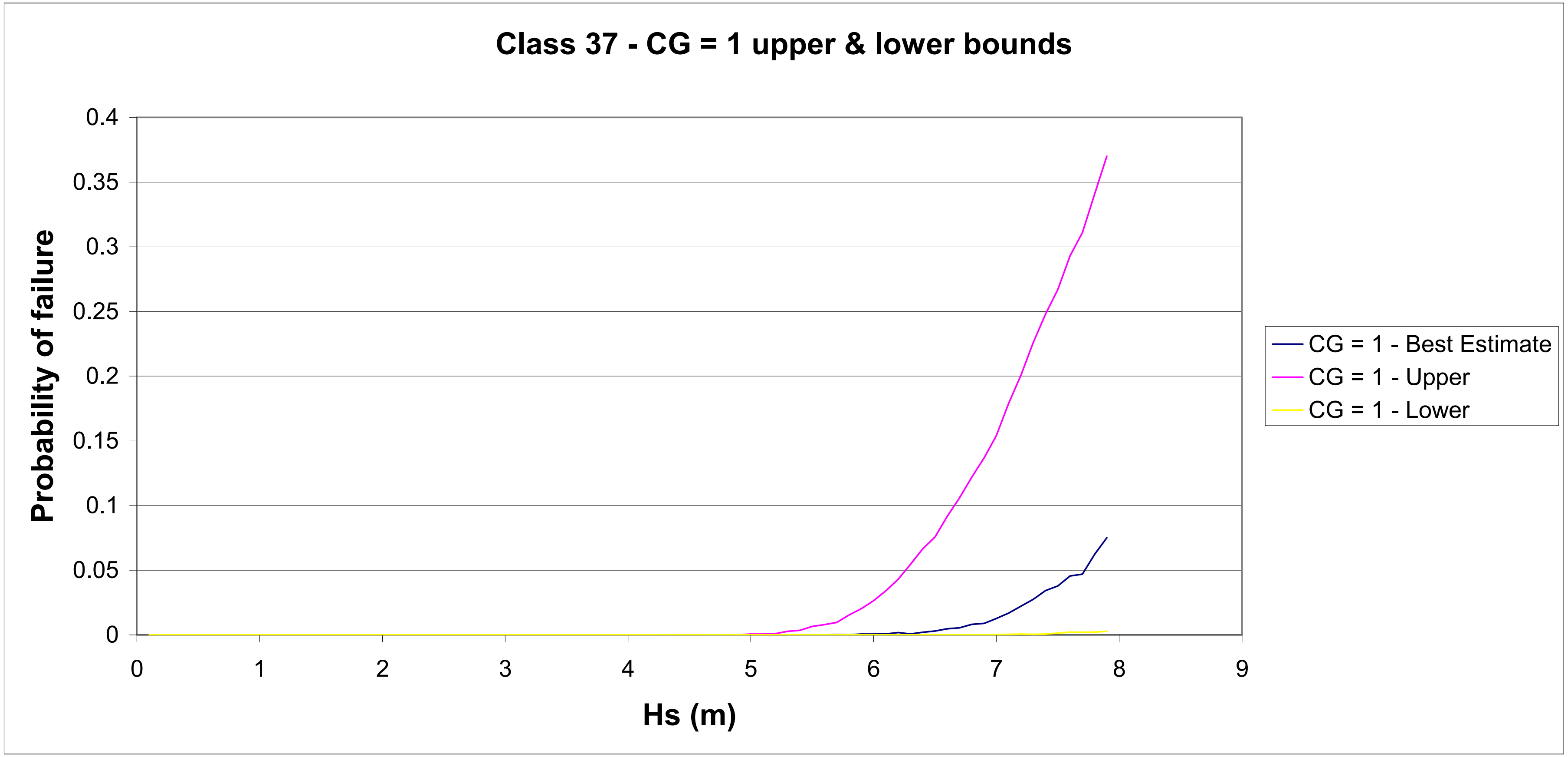

Class 33 - Best Estimate condition grades (Hs = 2m; Tp = 8s)
Probability of failure
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
-2.5
-2
-1.5
-1
-0.5
0
0.5
Difference between water level & crest level
CG = 1
CG = 2
CG = 3
CG = 4
CG = 5


Class 34 - Best Estimate condition grades Hs=2m; Tp=8s
Probability of failure
Difference between water level & crest level
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
-2.5
-2
-1.5
-1
-0.5
0
0.5
1
CG = 1
CG = 2
CG = 3
CG = 4
CG = 5


Class 35 - Best Estimate condition grades (Hs = 2m; Tp = 8s)
Probability of failure
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
-2.75
-2.25
-1.75
-1.25
-0.75
-0.25
0.25
0.75
Difference between water level & crest level
CG = 1
CG = 2
CG = 3
CG = 4
CG = 5

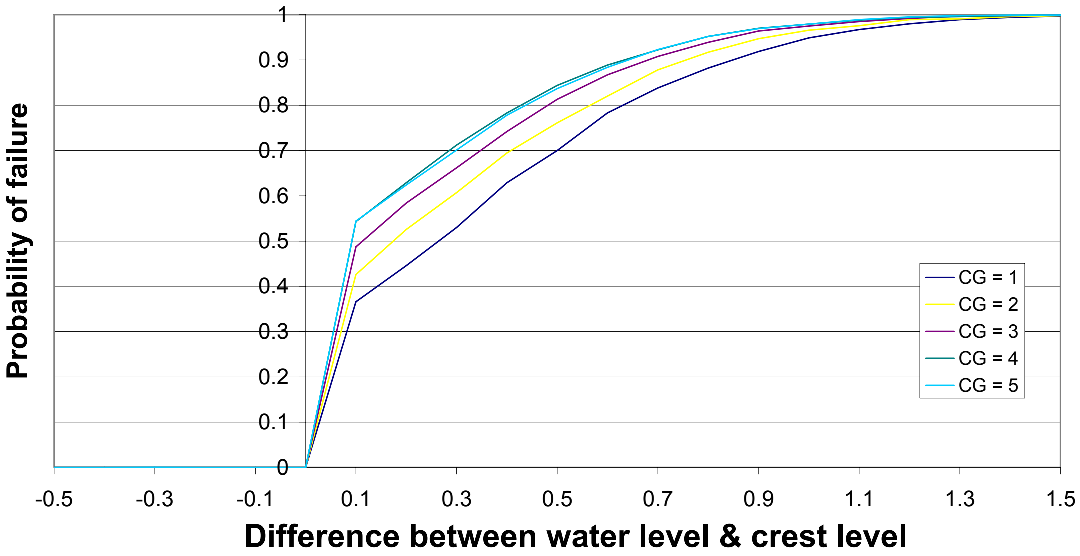

Class 36 - Best Estimate condition grades Hs = 2m; Tp = 8s
Probability of failure
Difference between water level & crest level
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
-2.5
-2
-1.5
-1
-0.5
0
0.5
1
CG = 1
CG = 2
CG = 3
CG = 4
CG = 5


Class 37 - Best Estimate condition grades
Probability of failure
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
0
1
2
3
4
5
6
7
8
9
HS (m)
Series1
Series2
Series3
Series4
Series5

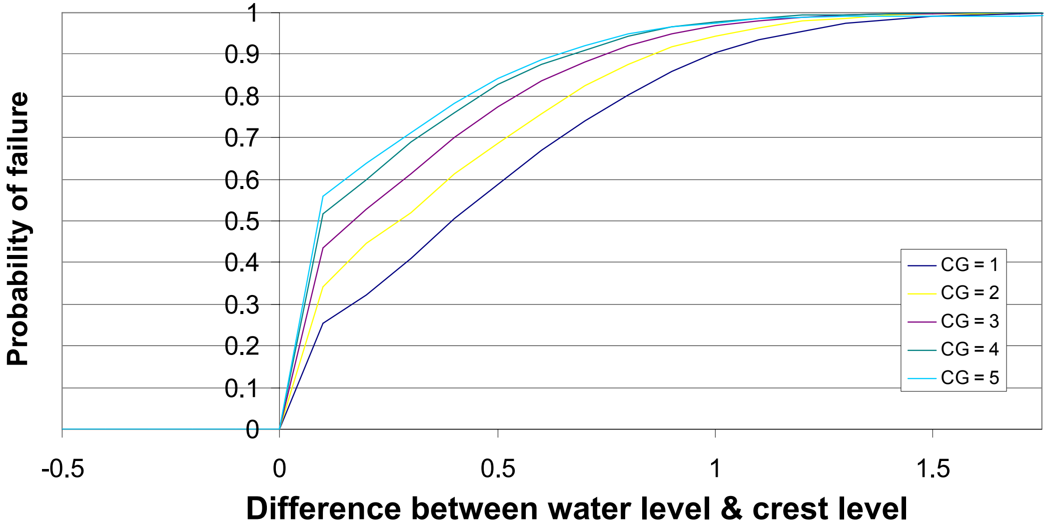


Fout! Ongeldige koppeling.Fout! Ongeldige koppeling.

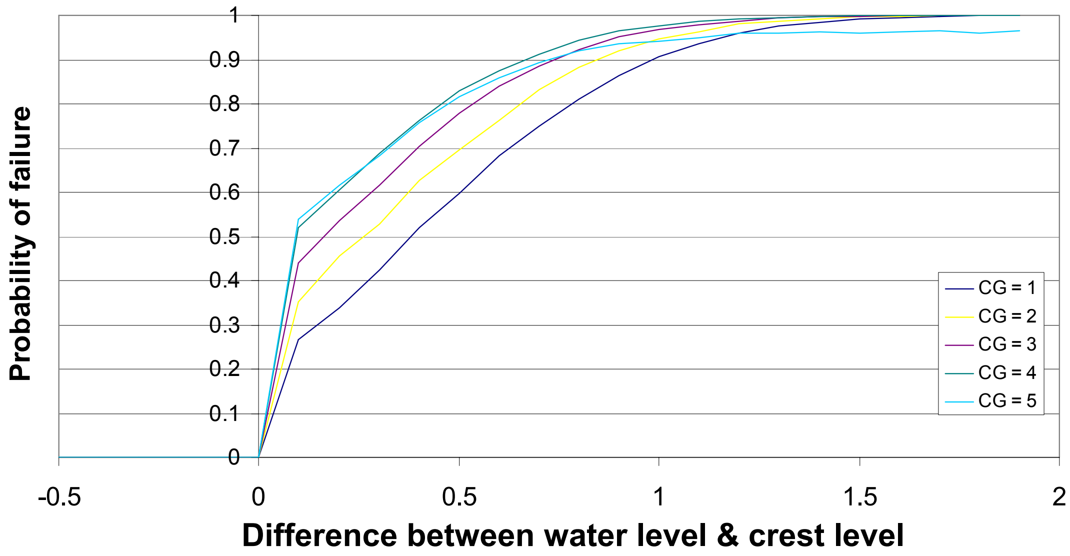
Class 39 – Best estimate condition grades



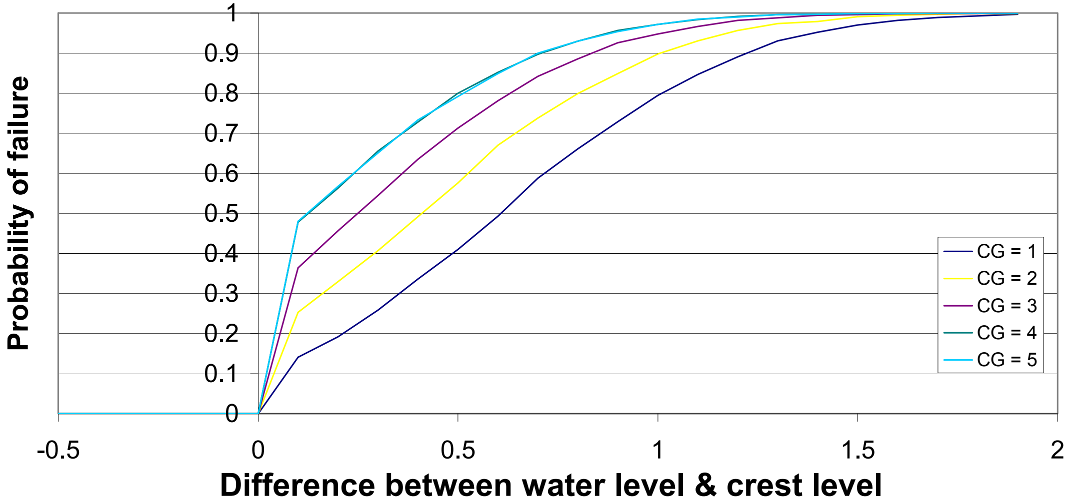
Class 40 – Best Estimate condition grades



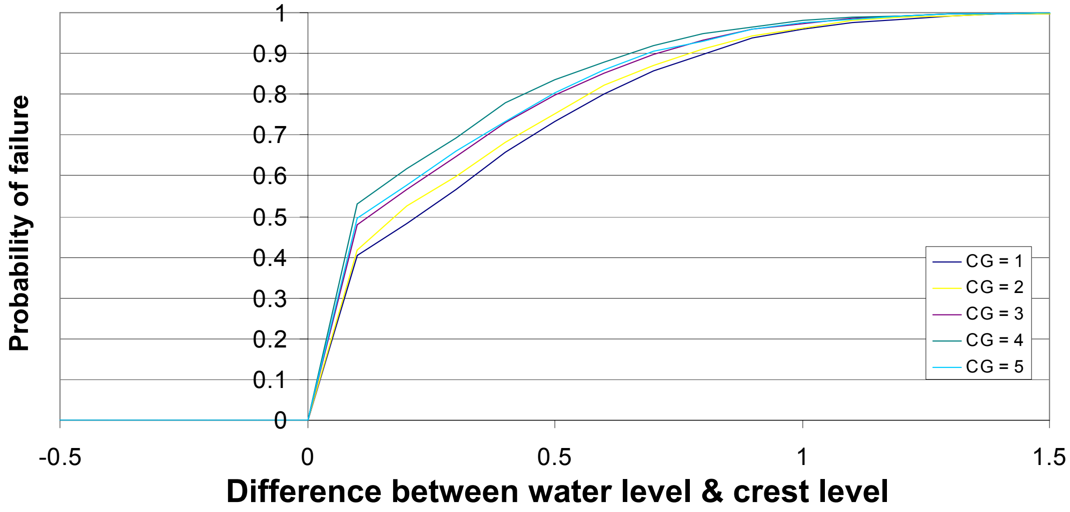
Class 41 – Best Estimate condition grades



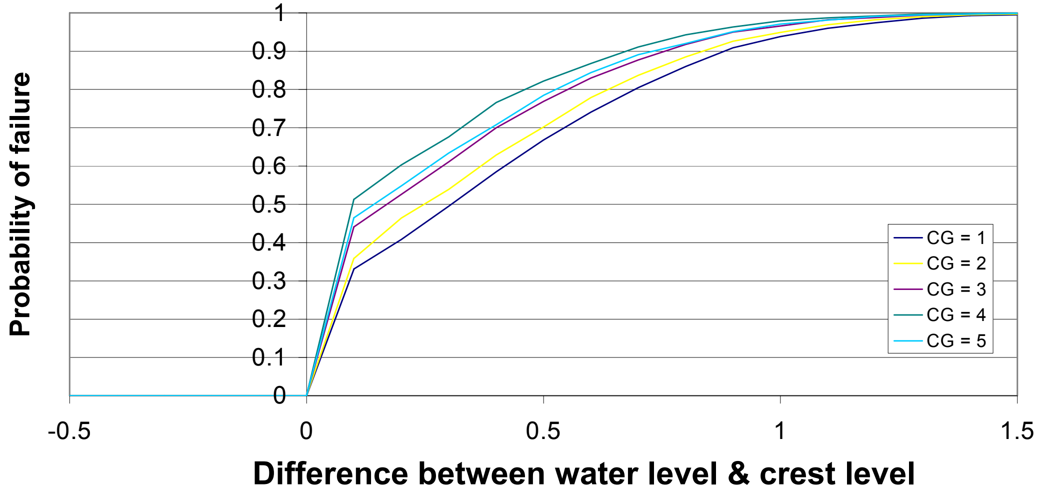
Class 42 – Best Estimate condition grades

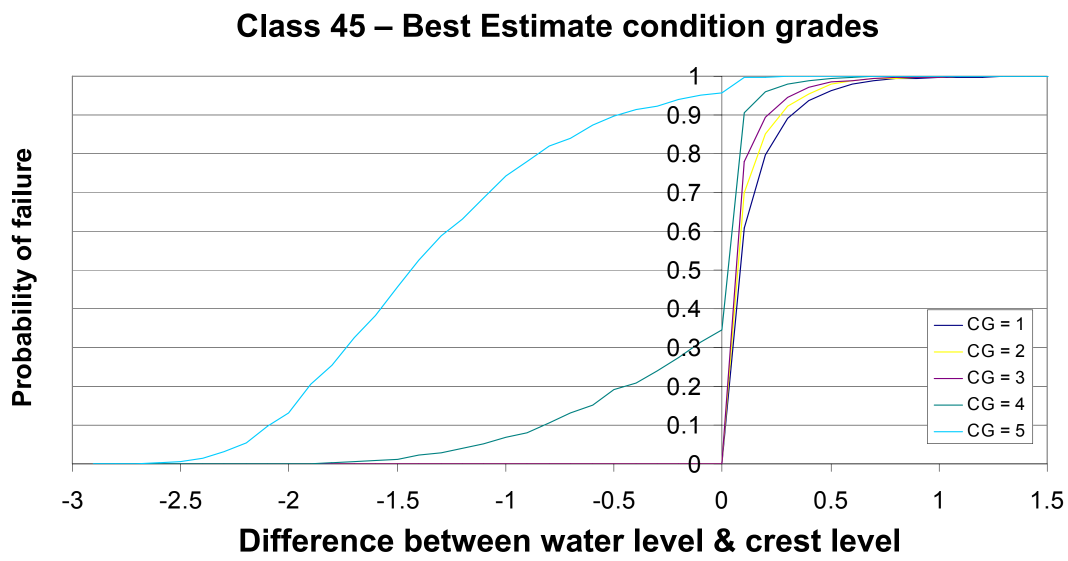


Class 43 – Best Estimate condition grades

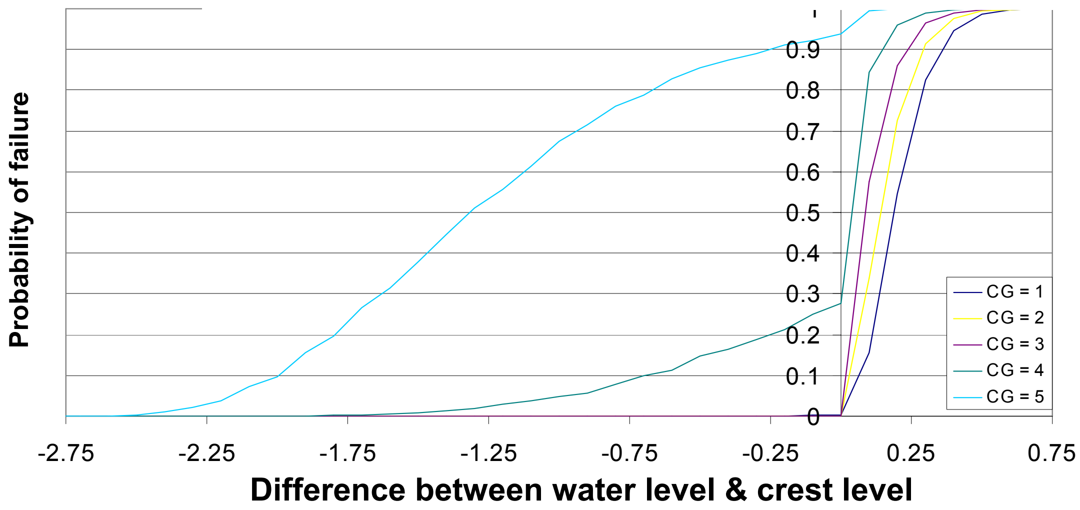


Class 44 – Best Estimate condition grades

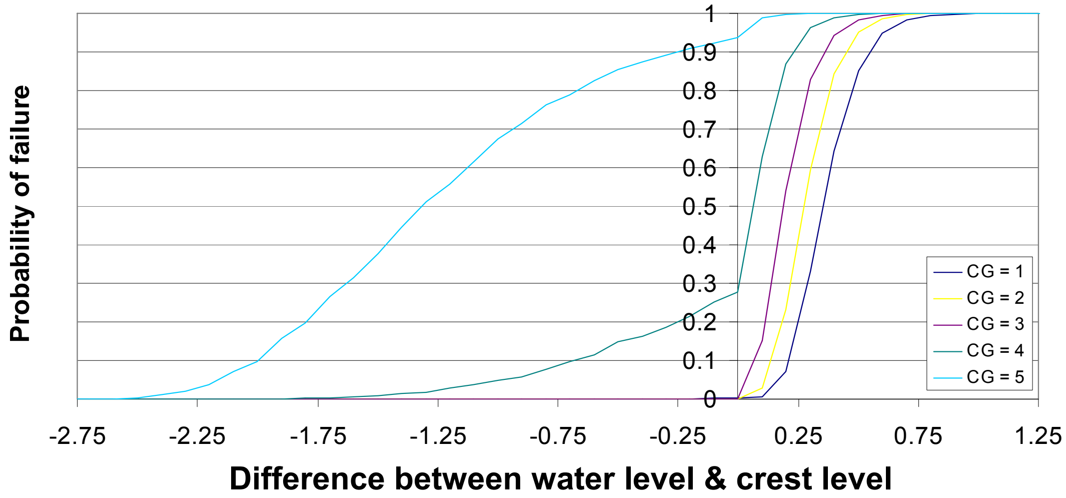



Class 45 – Best Estimate condition grades
Probability of failure
Difference between water level & crest level
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
-3
-2.5
-2
-1.5
-1
-0.5
0
0.5
1
1.5
CG = 1
CG = 2
CG = 3
CG = 4
CG = 5

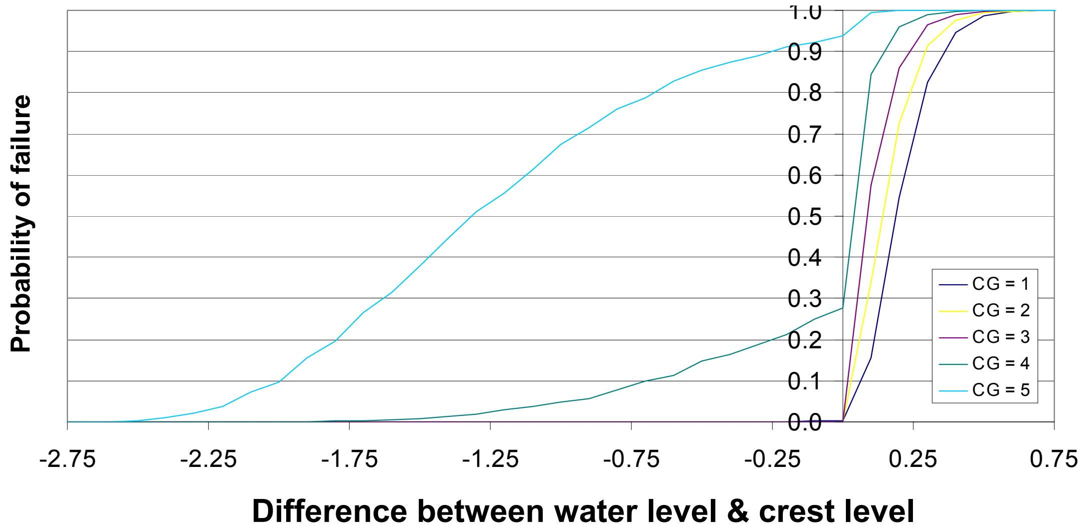
Class 46 – Best Estimate condition grades

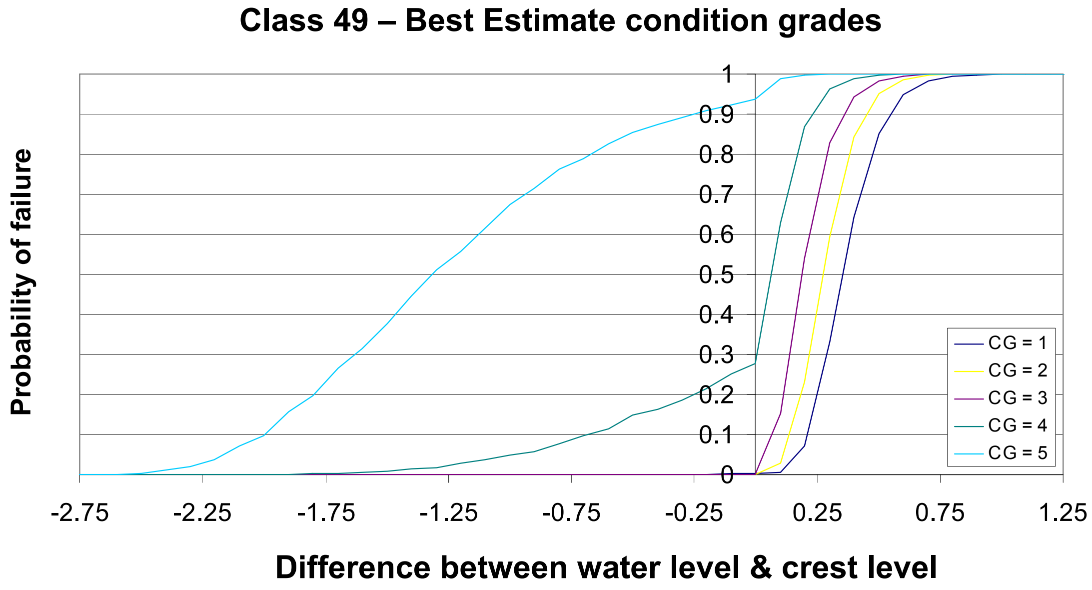


Class 47 – Best Estimate condition grades

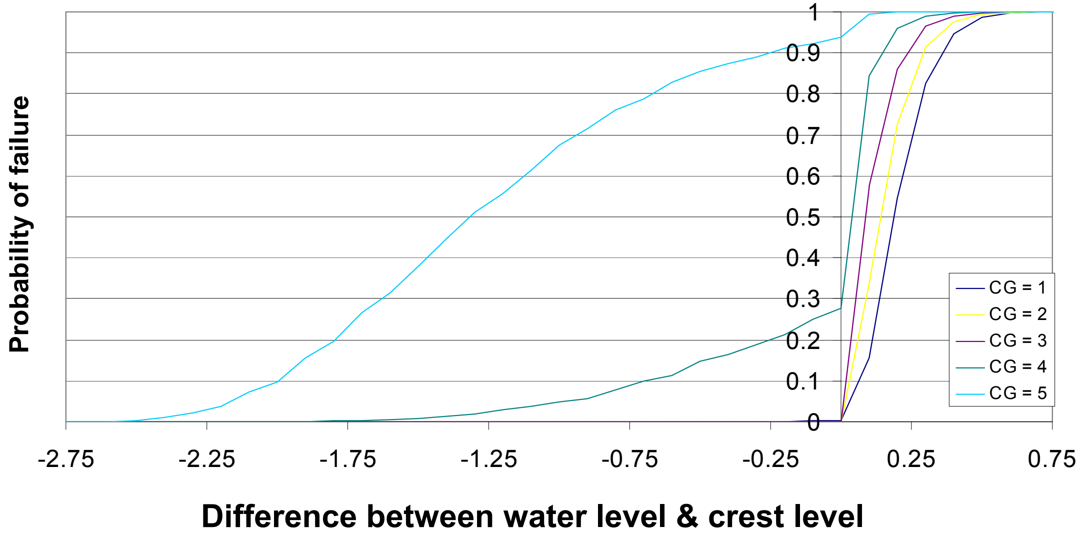


Class 48 – Best Estimate condition grades

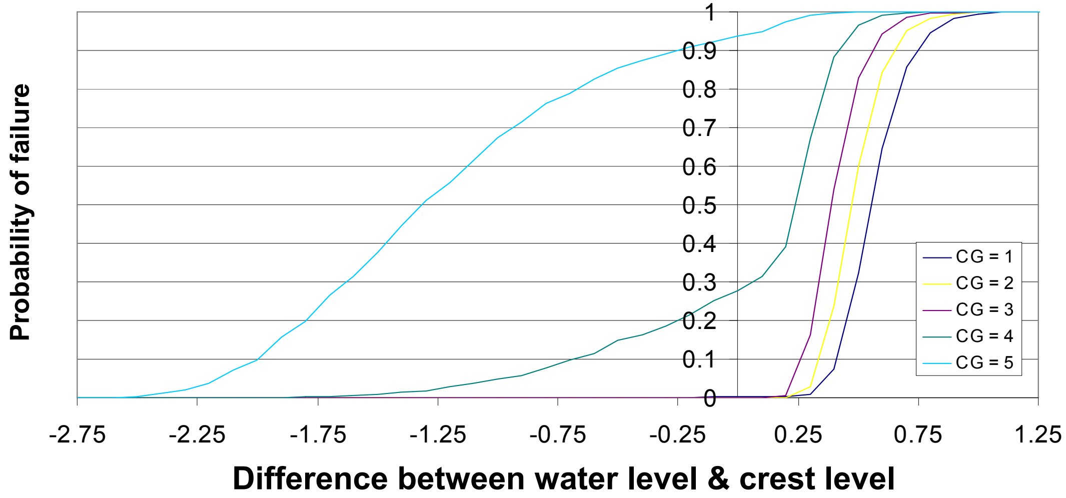


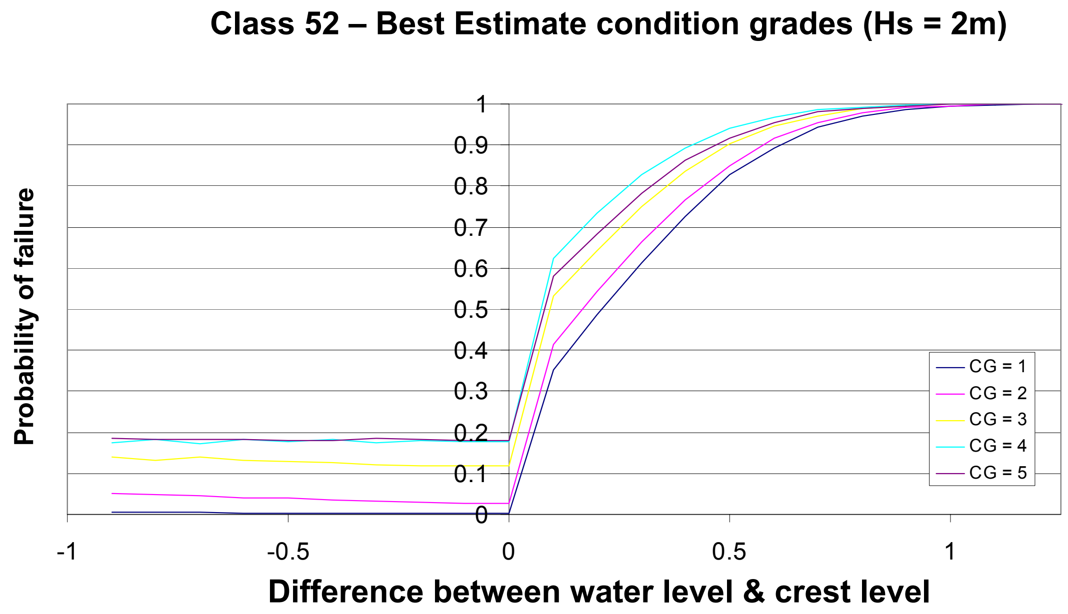

Class 49 – Best Estimate condition grades
Probability of failure
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
-2.75
-2.25
-1.75
-1.25
-0.75
-0.25
0.25
0.75
1.25
Difference between water level & crest level
CG = 1
CG = 2
CG = 3
CG = 4
CG = 5

Class 50 – Best Estimate condition grades

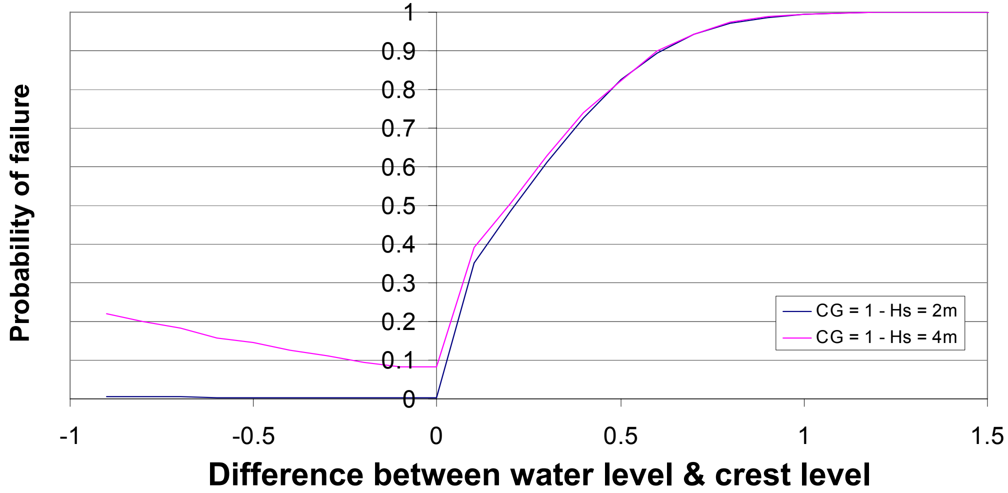


Class 51 – Best Estimate condition grades

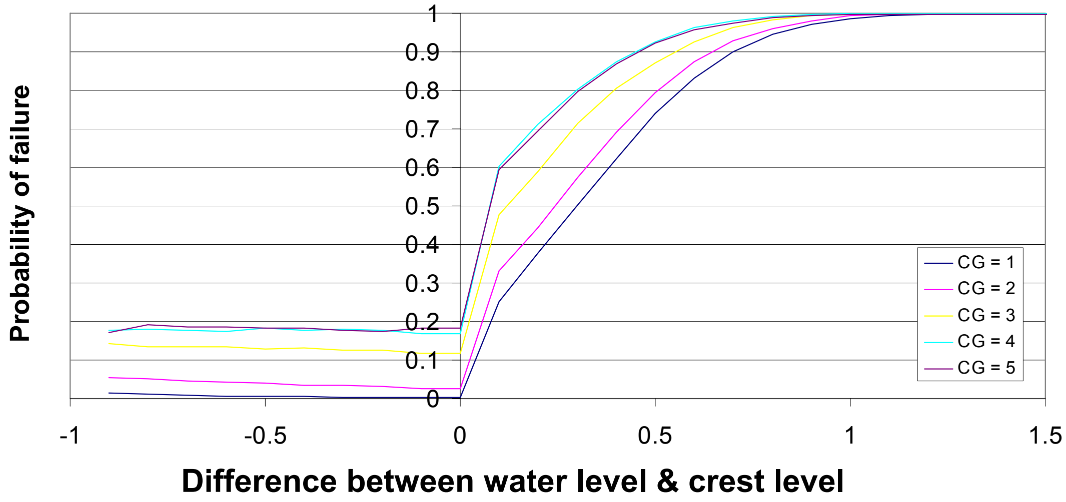


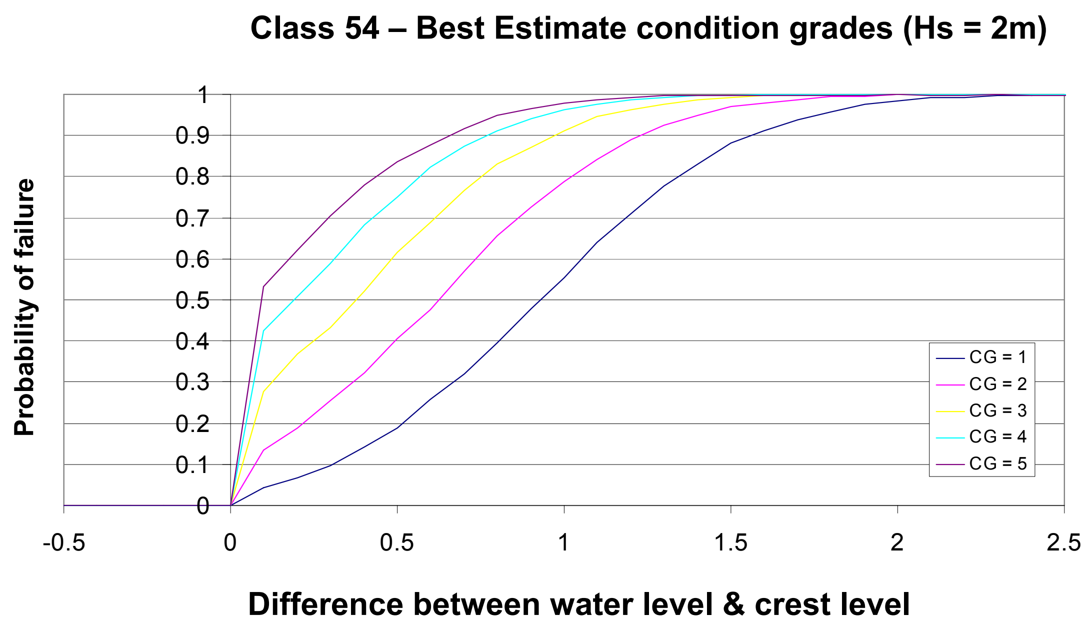

Class 52 – Best Estimate condition grades (Hs = 2m)
Probability of failure
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
-1
-0.5
0
0.5
1
Difference between water level & crest level
CG = 1
CG = 2
CG = 3
CG = 4
CG = 5

Class 52 – Comparison Hs = 2m and Hs = 4m

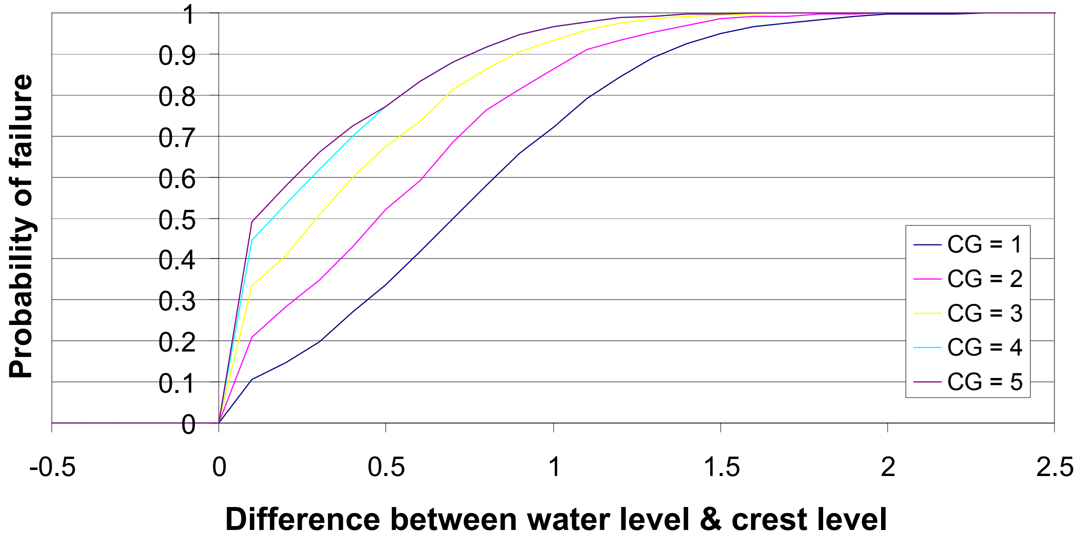


Class 53 – Best Estimate condition grades (Hs = 2m)

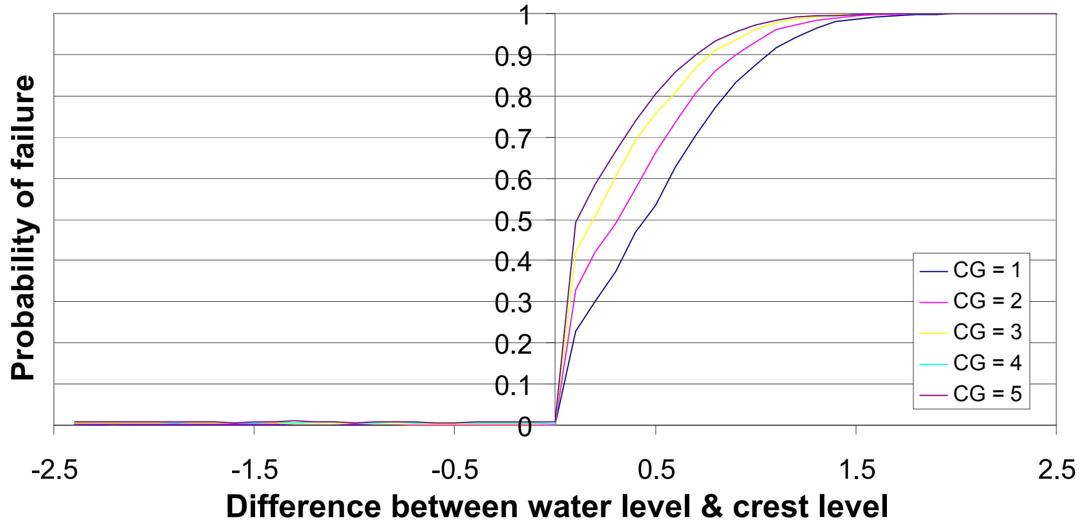



Class 54 – Best Estimate condition grades (Hs = 2m)
Probability of failure
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
-0.5
0
0.5
1
1.5
2
2.5
Difference between water level & crest level
CG = 1
CG = 2
CG = 3
CG = 4
CG = 5

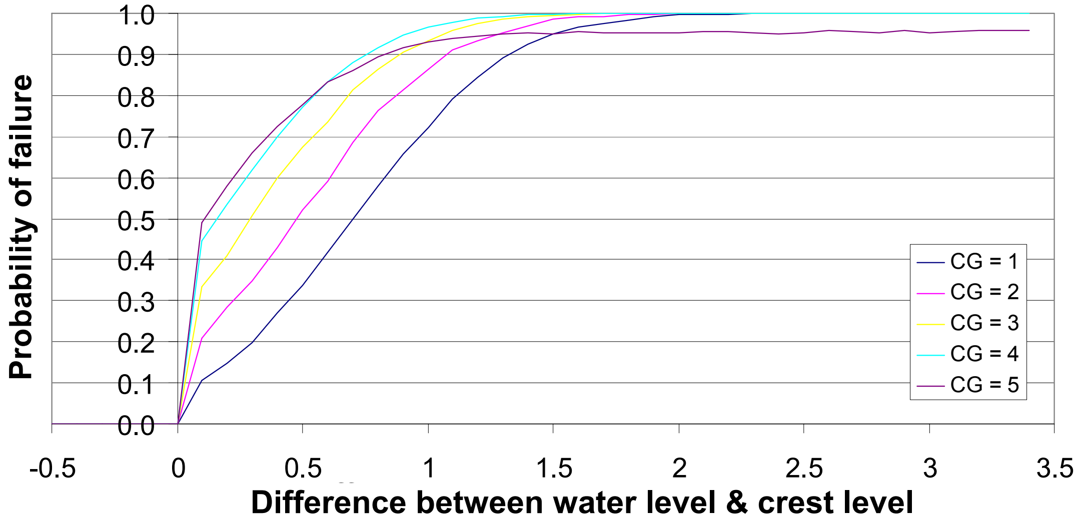
Class 55 – Best Estimate condition grades (Hs = 2m)



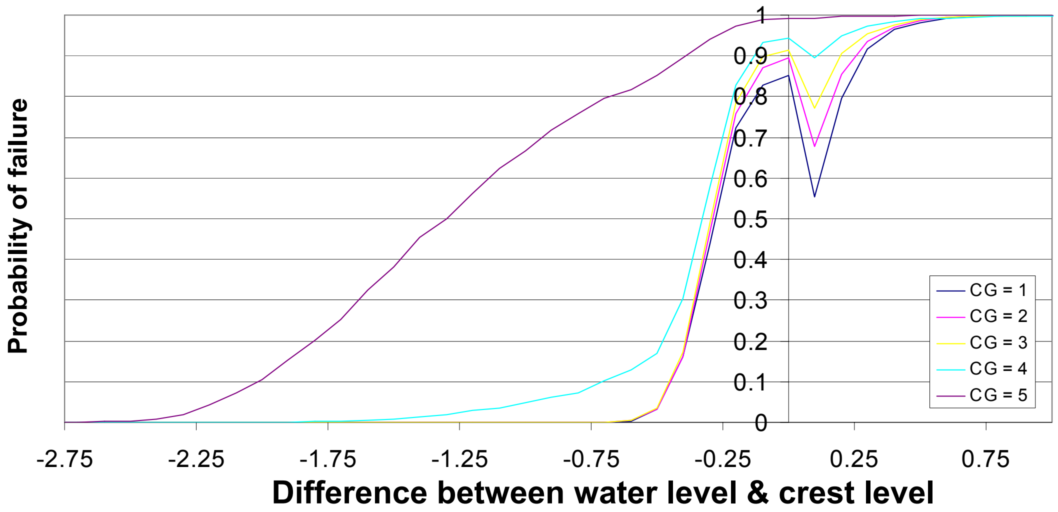
Class 56 – Best Estimate condition grades (Hs = 2m)



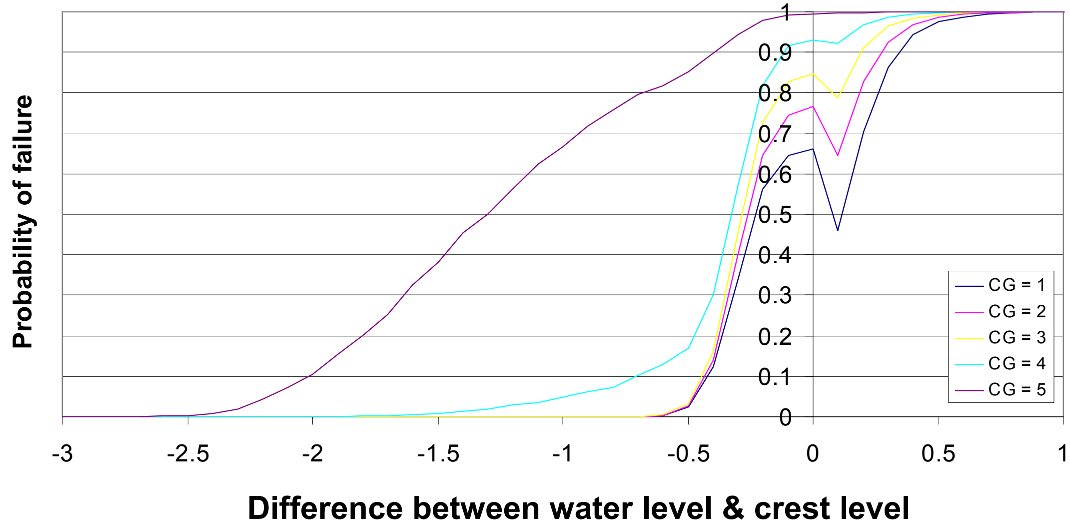
Class 57 – Best Estimate condition grades (Hs = 2m)

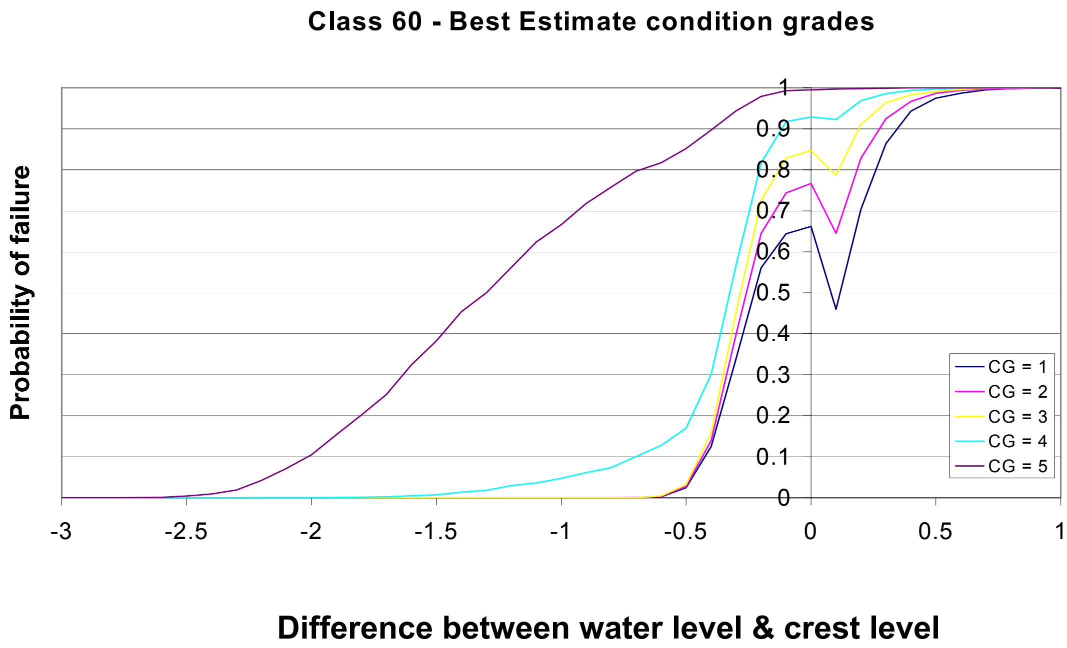


Class 58 – Best Estimate condition grades Hs = 2m; Tp

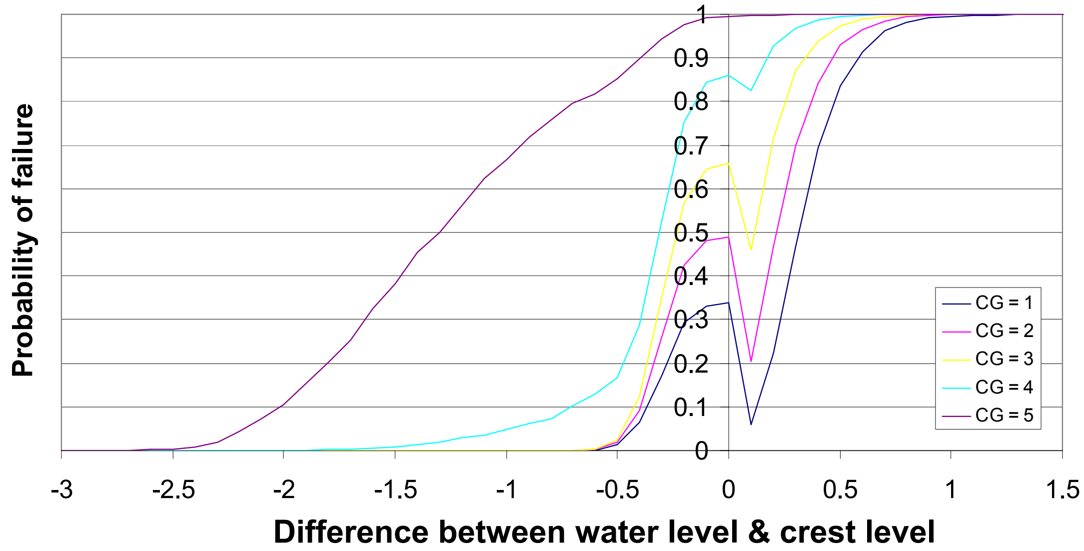


Class 59 – Best Estimate condition grades ~(Hs = 2m; Tp = 8s(




Class 60 - Best Estimate condition grades
Probability of failure
Difference between water level & crest level
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
-3
-2.5
-2
-1.5
-1
-0.5
0
0.5
1
CG = 1
CG = 2
CG = 3
CG = 4
CG = 5

Class 61 – Best Estimate condition grades



Appendix 6 Summary of Dominant Failure Modes

Narrow/Wide	FP	CP	RP	Coastal/Fluvial	Type	Material	Dominant failure modes	
Narrow	Y			Fluv	Vertical Wall	Gabion	Overturning due to toe scour & erosion of earth bank	Erosion due to flowing over
Narrow	Y	Y		Fluv	Vertical Wall	Gabion	Overturning due to toe scour & erosion of earth bank	Erosion due to flowing over
Narrow	Y	Y	Y	Fluv	Vertical Wall	Gabion	Overturning due to toe scour & erosion of earth bank	Erosion due to flowing over
Narrow	Y			Fluv	Vertical Wall	Brick & Masonry or Concrete	Overturning due to toe scour & erosion of earth bank	Erosion due to flowing over
Narrow	Y	Y		Fluv	Vertical Wall	Brick & Masonry or Concrete	Overturning due to toe scour & erosion of earth bank	Erosion due to flowing over
Narrow	Y	Y	Y	Fluv	Vertical Wall	Brick & Masonry or Concrete	Overturning due to toe scour & erosion of earth bank	Erosion due to flowing over
Narrow	Y			Fluv	Vertical Wall	Sheet Piles	Rotational failure due to toe scour & erosion of earth bank	Erosion due to flowing over
Narrow	Y	Y		Fluv	Vertical Wall	Sheet Piles	Rotational failure due to toe scour & erosion of earth bank	Erosion due to flowing over
Narrow	Y	Y	Y	Fluv	Vertical Wall	Sheet Piles	Rotational failure due to toe scour & erosion of earth bank	Erosion due to flowing over
Narrow				Fluv	Slopes or Embankments	Turf	Piping	Erosion due to flowing over
Narrow	Y			Fluv	Slopes or Embankments	Rigid	Piping	Erosion due to flowing over
Narrow	Y	Y		Fluv	Slopes or Embankments	Rigid	Piping	Erosion due to flowing over
Narrow	Y	Y	Y	Fluv	Slopes or Embankments	Rigid	Piping	Erosion due to flowing over
Narrow	Y			Fluv	Slopes or Embankments	Rip-rap	Piping	Erosion due to flowing over
Narrow	Y	Y		Fluv	Slopes or Embankments	Rip-rap	Piping	Erosion due to flowing over
Narrow	Y	Y	Y	Fluv	Slopes or Embankments	Rip-rap	Piping	Erosion due to flowing over
Narrow	Y			Fluv	Slopes or Embankments	Flexible	Piping	Erosion due to flowing over
Narrow	Y	Y		Fluv	Slopes or Embankments	Flexible	Piping	Erosion due to flowing over
Narrow	Y	Y	Y	Fluv	Slopes or Embankments	Flexible	Piping	Erosion due to flowing over
-				Fluv	High Ground		-	-
-				Fluv	Culvert			-
Narrow	Y			Coas	Vertical walls	Sheet piles	Rotational failure due to toe scour & erosion of earth bank	Erosion due to flowing over
Narrow	Y	Y		Coas	Vertical walls	Sheet piles	Rotational failure due to toe scour & erosion of earth bank	Erosion due to flowing over
Narrow	Y	Y	Y	Coas	Vertical walls	Sheet piles	Rotational failure due to toe scour & erosion of earth bank	Erosion due to flowing over
Narrow	Y			Coas	Vertical walls	Concrete	Overturning due to toe scour & erosion of earth bank	Erosion due to flowing over
Narrow	Y	Y		Coas	Vertical walls	Concrete	Overturning due to toe scour & erosion of earth bank	Erosion due to flowing over
Narrow	Y	Y	Y	Coas	Vertical walls	Concrete	Overturning due to toe scour & erosion of earth bank	Erosion due to flowing over
Narrow	Y			Coas	Vertical walls	Brick & Masonry	Overturning due to toe scour & erosion of earth bank	Erosion due to flowing over
Narrow	Y	Y		Coas	Vertical walls	Brick & Masonry	Overturning due to toe scour & erosion of earth bank	Erosion due to flowing over
Narrow	Y	Y	Y	Coas	Vertical walls	Brick & Masonry	Overturning due to toe scour & erosion of earth bank	Erosion due to flowing over
Narrow	Y			Coas	Dykes or embankments	Permeable revetment	Piping	Erosion due to overtopping / flowing over
Narrow	Y	Y		Coas	Dykes or embankments	Permeable revetment	Piping	Erosion due to overtopping / flowing over
Narrow	Y	Y	Y	Coas	Dykes or embankments	Permeable revetment	Piping	Erosion due to overtopping / flowing over
Narrow	Y			Coas	Dykes or embankments	Impermeable revetment	Piping	Erosion due to overtopping / flowing over
Narrow	Y	Y		Coas	Dykes or embankments	Impermeable revetment	Piping	Erosion due to overtopping / flowing over
Narrow	Y	Y	Y	Coas	Dykes or embankments	Impermeable revetment	Piping	Erosion due to overtopping / flowing over
-				Coas	Beaches		Exceedance of crest width	Exceedance acceptable overtopping
-				Coas	Beaches		Exceedance of crest width	Exceedance acceptable overtopping
Wide	Y			Fluv	Vertical Wall	Gabions	Overturning due to toe scour & erosion of earth bank	Erosion due to flowing over
Wide	Y	Y		Fluv	Vertical Wall	Gabions	Overturning due to toe scour & erosion of earth bank	Erosion due to flowing over
Wide	Y			Fluv	Vertical Wall	Brick & Masonry or Concrete	Overturning due to toe scour & erosion of earth bank	Erosion due to flowing over
Wide	Y	Y		Fluv	Vertical Wall	Brick & Masonry or Concrete	Overturning due to toe scour & erosion of earth bank	Erosion due to flowing over
Wide	Y			Fluv	Vertical Wall	Sheet piles	Rotational failure due to toe scour & erosion of earth bank	Erosion due to flowing over
Wide	Y	Y		Fluv	Vertical Wall	Sheet piles	Rotational failure due to toe scour & erosion of earth bank	Erosion due to flowing over
Wide				Fluv	Slopes or Embankments	Turf	Piping	Erosion due to flowing over
Wide	Y			Fluv	Slopes or Embankments	Rigid	Piping	Erosion due to flowing over
Wide	Y	Y		Fluv	Slopes or Embankments	Rigid	Piping	Erosion due to flowing over
Wide	Y			Fluv	Slopes or Embankments	Rip-rap	Piping	Erosion due to flowing over
Wide	Y	Y		Fluv	Slopes or Embankments	Rip-rap	Piping	Erosion due to flowing over
Wide	Y			Fluv	Slopes or Embankments	Flexible	Piping	Erosion due to flowing over
Wide	Y	Y		Fluv	Slopes or Embankments	Flexible	Piping	Erosion due to flowing over
Wide	Y			Coas	Vertical walls	Sheet piles	Rotational failure due to toe scour & erosion of earth bank	Erosion due to flowing over
Wide	Y	Y		Coas	Vertical walls	Sheet piles	Rotational failure due to toe scour & erosion of earth bank	Erosion due to flowing over
Wide	Y			Coas	Vertical walls	Concrete	Overturning due to toe scour & erosion of earth bank	Erosion due to flowing over
Wide	Y	Y		Coas	Vertical walls	Concrete	Overturning due to toe scour & erosion of earth bank	Erosion due to flowing over
Wide	Y			Coas	Vertical walls	Brick & Masonry	Overturning due to toe scour & erosion of earth bank	Erosion due to flowing over
Wide	Y	Y		Coas	Vertical walls	Brick & Masonry	Overturning due to toe scour & erosion of earth bank	Erosion due to flowing over
Wide	Y			Coas	Dykes or embankments	Permeable revetment	Piping	Erosion due to overtopping / flowing over
Wide	Y	Y		Coas	Dykes or embankments	Permeable revetment	Piping	Erosion due to overtopping / flowing over
Wide	Y			Coas	Dykes or embankments	Impermeable revetment	Piping	Erosion due to overtopping / flowing over
Wide	Y	Y		Coas	Dykes or embankments	Impermeable revetment	Piping	Erosion due to overtopping / flowing over

Appendix 7 Data Requirements

Symbol	Dimension	Description	Statistical distribution function	Mean value	stdv (=s) or variation coefficient (=v)
h	[m]	water level (with respect to the bottom level)	deterministic in fragility	variable	variable
Hs	[m]	significant wave height	deterministic in fragility	variable	variable
Tp	[s]	peak wave period	deterministic in fragility	variable	variable
hc	[m]	crest level (with respect to the bottom level)	normal	4.5	V = 0.1
cw	[m]	crest width	lognormal	variable	V = 0.25
tano	[-]	tan outside slope	normal	0.33	V = 0.05
tani	[-]	tan inside slope	normal	0.33	V = 0.05
cg	[ms]	erosion strength grass	lognormal	1000000	V = 0.3
cRK	[ms]	erosion strength core	lognormal	34000	V = 0.3
dw	[m]	depth grass roots	lognormal	0.2	V = 0.2
Pt	[-]	pulsating percentage	deterministic	0.5 (wave overtop) / 1 (flowing over)	-
r_i	[m]	roughness inside slope	lognormal	0.015	V = 0.01
ts	[h]	storm duration	lognormal	12 (fluvial) / 7 (coastal)	V = 12
m_qe	[-]	model uncertainty erosion model	lognormal	depends on class / condition grade	V = 0.1
r_o	[-]	roughness outside slope	lognormal	1	s = 0.01
beta	[°]	obliqueness waves	normal	0	s = 1
A	[-]	coefficient Owen's model	lognormal	0.0109	V = 0.1
B	[-]	idem	lognormal	28.7	V = 0.2
m_qo	[-]	model uncertainty owen's model	lognormal	1	V = 0.1
Dimp	[m]	thickness impermeable layers	normal	3	V = 0.3
gamma_wet	[kN/m^3]	saturated density of the soil	normal	18	0.05
gamma_w	[kN/m^3]	density of the water	deterministic	10	-
fg	[m]	depth ground water level below ground	deterministic	0.5	-
Lv	[m]	vertical seepage length	normal	0	s = 0.1
Lh	[m]	horizontal seepage length	normal	depends on class / condition grade	V = 0.2
cT	[-]	Creep ratio, Terzaghi	lognormal	depends on class / condition grade	V = 0.05
m_t	[-]	model uncertainty Terzaghi	lognormal	1	V = 0.1
riv	[-]	river or coast scour model	deterministic	0 (coastal) / 1 (fluvial)	-
H_s	[m]	height structure between ground level and bottom level	normal	4.5	V = 0.1
d	[m]	depth toe	normal	1.5	V = 0.1
Ka	[-]	coefficient horizontal grain stress; active	lognormal	0.33	
Kp	[-]	coefficient horizontal grain stress; passive	lognormal	3	
d_a	[m]	depth anchors	normal	0.8	V = 0.01
mspar_R	[-]	model uncertainty rotation anchored sheet pile - R	lognormal	1	V = 0.1
mspar_S	[-]	model uncertainty rotation anchored sheet pile - S	lognormal	1	V = 0.1
angle	[°]	angle of inclination anchors	normal	30	s = 5
no_anch	[-]	average number of anchors per stretching meter	det	1	-
rad	[m]	radius of anchors	lognormal	0.06	V = 0.01
mspas_R	[-]	model uncertainty anchored sheet pile snapping - R	lognormal	1	V = 0.1
mspas_S	[-]	model uncertainty anchored sheet pile snapping - S	lognormal	1	V = 0.1
mspcr_R	[-]	model uncertainty cantilever sheet pile rotation - R	lognormal	1	V = 0.1
mspcr_S	[-]	model uncertainty cantilever sheet pile rotation - S	lognormal	1	V = 0.1
H_c	[m]	total height gravity based structure	normal	6	V = 0.1
Ba	[m]	base gravity based structure	normal	2	V = 0.1
gamma_c	[kN/m^3]	density material of gravity based structure	lognormal	depends on class	V = 0.15
delta	[°]	friction angle	normal	40	V = 0.1
mgbo_R	[-]	model uncertainty gravity-based wall sliding - R	lognormal	1	V = 0.1
mgbo_S	[-]	model uncertainty gravity-based wall sliding - S	lognormal	1	V = 0.1
mgbo_R	[-]	model uncertainty gravity-based wall overturning - R	lognormal	1	V = 0.1
mgbo_S	[-]	model uncertainty gravity-based wall overturning - S	lognormal	1	V = 0.1
m_shw	[-]	model uncertainty width shingle beach	lognormal	1	V = 0.1
sh_width	[m]	shingle beach width	normal	15	V=0.25
Db	[m]	effective beach width	normal	depends on condition grade	V=0.26
mshret	[-]	model uncertainty shingle retreat	lognormal	1	V = 0.1
D50	[m]	D50 shingle	lognormal	depends on class	V = 0.1
Q_ac_sh	[m^3/s]	acceptable overtopping shingle beach	deterministic	1	-
m_q_sh	[-]	model uncertainty overtopping shingle	lognormal	1	V = 0.1
betar	[°]	angle oblique waves for reduction factor	normal	0	s = 1
gamma_s1	[kN/m^3]	saturated density soil behind vertical walls	normal	18	V = 0.1
gamma_d1	[kN/m^3]	dry density of soil behind the vertical walls	normal	16	V = 0.1

Crest width			
	Best Estimate	Upper bound	Lower bound
Narrow	7.5	2	10
Wide	20	15	25

Storm duration	
Fluvial	12
Coastal	7

Strength multiplication factors in overflow failure mode		
Structure types	Gabions	1.5
	Concrete / brick & masonry	3
	Sheet piles	2.5
Revetments	Front protection	1
	Front + crest protection	1.5
	Front + crest + rear protection	2

Strength multiplication factors for failure modes in general		
Condition grades	Cg =1	1
	Cg =2	0.8
	Cg =3	0.6
	Cg =4	0.4
	Cg =5	0.2

Piping condition grades			
	Seepage length		Creep ratio
	narrow	wide	
Cg =1	60	100	6
Cg =2	60	100	6
Cg =3	60	100	6
Cg =4	10	30	8
Cg =5	6	24	15

Material densities (kN/m^3)	
Gabions	16
Brick & Masonry	20
Concrete	23

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