delivering benefits through evidence

Modes of dam failure and monitoring and measuring techniques

Project: SC080048/R1

Flood and Coastal Erosion Risk Management Research and Development Programme

Current research projects are being carried out by the Environment Agency and Defra following a review of research priorities and direction by the Reservoir Safety Advisory Group (RSAG) of the Institution of Civil Engineers (ICE).

The British Dam Society at the Institution of Civil Engineers

The British Dam Society aspires to be a forum for professionals involved with dams to meet and exchange ideas and to be a body of people with authority and/or interest on dam-related issues. It monitors and contributes to the agenda on the provision of technical guidance and wider research on dams for the UK and also promotes best practice in all aspects of the planning, development, maintenance and operation of dams and reservoirs.

In this context it is pleased to support the Environment Agency's production of this report as part of a programme of carefully targeted research aimed at improving the understanding of dam related issues and also the safety of the UK's stock of reservoirs, however, this does not imply endorsement of any particular report recommendations.

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This report was produced by the Research, Monitoring and Innovation team within Evidence. The team focuses on four main areas of activity:

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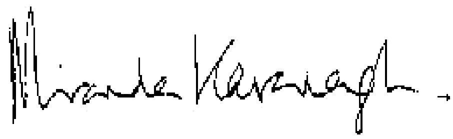

Miranda Kavanagh

Director of Evidence

Executive summary

The Department for Environment, Food and Rural Affairs (Defra) Reservoir Safety Research and Development Strategy identified priority areas for research projects that would draw together best practice, operational experience and recent developments in the management of existing UK dams. This scoping study focuses on the modes of failure of dams and monitoring techniques, and on methods to monitor and measure embankment dams (other dams are also considered).

Environment Agency reservoir safety work provides an opportunity to make the link between small embankment dams and flood embankments built for flood-risk management. The main objectives of the scoping study are:

- to establish what existing research there is in these two areas;
- to identify the appetite within the reservoir community for further research;
- through a gap-analysis process identify and specify any viable further science projects or other activities needed to secure appropriate and/or improved guidance to UK dam practitioners in these research areas.

One of the key aims is to understand the needs of the reservoir community in terms of further research. The methodology therefore focused on communication with a number of experts in the field through a questionnaire and workshop. Reservoir owners and managers, supervising engineers and all reservoir panel engineers participated and a panel of experts helped steer the project. Published and unpublished literature and projects were reviewed and presentations made to the British Dam Society and at a workshop for the associated Scoping Study for a Guide to Risk Assessment of Reservoirs. The work on modes of failure and monitoring and measuring techniques is also relevant to a number of other initiatives recommended in the Defra research and development (R&D) strategy.

A number of definitions and terms are provided in the report, but the terminology in any new guidance must be consistent and a review may be required as part of the overall research strategy.

After a review of the various models used for risk assessment, a simple method was adopted that will fit into any model for risk assessment. The first point on an event tree is a ‘threat’ (could also be called an initiating event or ‘source’ of a failure). From the threat a ‘hazard’ may result. For example, the threat of extreme rainfall and/or snow and the resulting flood may lead to the spillway capacity being exceeded, which thus forms a hazard. This hazard may or may not lead to the development of a ‘mode of failure’ that results in failure of the dam. In this example, if the embankment eroded as a result of the spillway capacity being exceeded, the mode of failure is dam breach.

If it is possible to monitor or measure the hazards that may impact on any particular dam, then in theory it is possible to identify a potential failure in advance of that failure occurring. A number of indicators in different locations within an embankment dam could be used to determine whether or not a hazard, and potentially a mode of failure, is developing.

The 48 hazards defined may lead to the following modes of failure:

- catastrophic overtopping;
- dam breach;
- foundation failure of a concrete dam;
- foundation failure of an embankment dam;
- instability of concrete dam;
- instability of embankment dam;
- overflow failure;

- structural failure of concrete dam;
- structural failure of embankment dam (deterioration of core);
- structural failure of embankment dam (load exceeded);
- uncontrolled flow due to appurtenant works failure;
- uncontrolled seepage.

Many of these hazards are covered by existing publications, although some require updating. Some modifications are required to the research projects identified in the Defra strategy and some new research projects are proposed.

A review of existing information on monitoring and measuring methods for embankment dams and general monitoring techniques for all dams found that the methods are generally well documented. However, many monitoring techniques are implemented without a full understanding of their capabilities and purpose and they are not always able to detect failure in advance of an incident. Furthermore, there are some techniques for which the reservoir community requires further guidance, such as seepage monitoring, leakage detection and remote sensing techniques [e.g., light detection and ranging (LiDAR), aerial photographs and satellite imagery].

Results of the scoping study indicate a number of areas in which further research or guidance would be useful to the reservoir profession:

- immediate actions – existing research can be used immediately by the reservoir safety profession or can be used after some minor development work;
- augmented or revised R&D – areas already partly covered within the Defra Reservoir Safety Research and Development Strategy, but for which additional information should be considered when these projects are implemented;
- new R&D proposals where required;
- low-to-medium priority new guidance – areas for which guidance is required, but only after current or planned research (these are in addition to those topics already covered in the Defra strategy).

A series of Reservoir Technical Guidance Notes can be produced immediately using existing information. These should cover surface erosion, upstream membranes and concrete–asphaltic facing, crest fissuring and controlled holding of water at a low level. Recommendations are made for augmentations of or revisions to projects already listed in the Defra strategy.

The highest priority projects recommended for R&D proposals are:

- reservoirs and ecological hazards: a best practice guide to the management of animals and vegetation;
- reservoir safety: a checklist for surveillance;
- modes of failure of dams – trial risk assessment (this should be completed as part of the 'guide to risk assessment' project);
- medium to high priority projects recommended are:
- monitoring techniques for different indicators;
- risk management of reservoirs – a best practice guide;
- reservoir engineering design to Eurocodes: draft guide for consultation.

The recommendations are made as a result of this scoping study and will only be implemented if they fulfil all criteria required for such projects. The recommendations may be modified or combined to fulfil the requirements of the Defra Reservoir Safety Research and Development Strategy (2009) or other related programmes of research. Some of the work proposed in these recommendations may be incorporated into existing studies. It is not possible to confirm at this time which, if any, of these recommendations will be taken forward.

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The authors gratefully acknowledge the support a Panel of Experts in completing this study: Mr Jim Claydon, Mr Kenny Dempster, Mr Henry Hewlett and Mr Paul Tedd. The authors are also extremely grateful for input from other members of the reservoir community in the UK. A number of reservoir owners, managers, supervising engineers, all reservoir panel engineers and interested parties contributed to questionnaires and a workshop as part of this study.

Contents

1 Introduction

1.1 Background

1.1.1 Scope of study

The Department for Environment, Food and Rural Affairs (Defra) Reservoir Safety Research and Development Strategy (2009) identified priority areas for research projects that would draw together best practice, operational experience and recent developments in the management of existing UK dams. These research areas were put forward to the Sustainable Asset Management (SAM) Theme Advisory Group (TAG) of the Joint Defra–Environment Agency Flood and Coastal Erosion Risk Management (FCERM) research and development (R&D) programme. They were also presented to the Reservoir Safety Advisory Group, which gave its full support. Two of these areas are the focus of this scoping study:

- modes of failure of dams and failure of monitoring techniques;
- methods to monitor and measure embankment dams.

SAM TAG identified that for both topics some research already exists. One of the reasons for a scoping study to be carried out prior to any research in these areas is to avoid future studies that duplicate this work.

These two priority areas were grouped under one scoping project as they draw on similar conceptual and technical frameworks in terms of behaviour and modes of failure of the dam, and indicators of its performance. Also, the majority of dams that are the prime beneficiaries of Environment Agency reservoir safety research are embankments; of the 2094 dams in England and Wales subject to the Reservoirs Act 1975, at least 79 per cent are embankments. The scoping project does, however, aim to consider all types of dam known to exist in England and Wales.

This reservoir safety work provides an opportunity to make the link between small embankment dams and flood embankments built for flood-risk management. These structures share some of the same engineering principles, and benefits can be extracted from reservoir safety research applicable to both.

The main objectives of the scoping study are:

i. to establish what existing research there is in these two areas;

ii. to identify the appetite within the reservoir community for further research;

iii. through a gap-analysis process identify and specify any viable further science projects or other activities needed to secure appropriate and/or improved guidance to UK dam practitioners in these research areas.

The study is intended to highlight areas in which the existing Joint Programme Flood Embankment Research and Development can be utilised immediately by the reservoir safety profession or can be utilised after some minor development work.

The reservoirs in England and Wales subject to the Reservoir Act involve 759 undertakers, 75 per cent of whom only own one reservoir. The Flood and Water Management Act was published on 8 April 2010 and amends the Reservoirs Act. The amendments include that the minimum capacity of raised reservoirs is reduced from 25,000 cubic metres to 10,000 cubic metres. The implications of this are a number of new ‘reservoir managers’ are likely, who will need to understand their duties in the interest of reservoir safety, and that a significant number of structures will be legislated for the first time.

The types of dam covered by this scoping study include:

- buttress and earthfill
- concrete buttress
- masonry buttress
- earthfill
- earthfill and rockfill
- rockfill
- gravity and arch
- gravity and buttress
- gravity and earthfill
- gravity and rockfill
- concrete gravity
- masonry gravity
- prestressed concrete
- roller compacted concrete
- tailings
- concrete arch

These are dam types included in the Environment Agency database of reservoirs in England and Wales. Watertight elements are listed as being asphaltic, concrete, earthfill, metal, plastic, puddle clay, rolled clay, other or not known.

1.1.2 Methodology

One of the key aims of this scoping study is to understand the appetite within the reservoir community for further research into the areas identified in section 1.1.1. The methodology for completing the study therefore focused on communication with a number of experts in the field and comprised:

- review of published and unpublished literature and/or projects (see References);
- meeting and on-going discussion with a panel of experts;
- questionnaire sent to 170 individuals, with responses received from
  - three reservoir owners
  - three reservoir managers
  - 14 supervising engineers
  - 14 all reservoir panel engineers
  - six others;
- presentations and discussions at workshops outside the scope of this study:
  - British Dam Society (BDS) meeting, 23 February 2009
  - Scoping Study for a Guide to Risk Assessment, 31 March 2009
  - Supervising Engineers’ Forum, 22 April 2009
- workshop to communicate findings of the study and provide further opportunity for input, 21 May 2009.

In researching the topics, much of the existing information was found in a number of key documents, discussed in Section 1.4 below. The report aims to identify where this information is sufficient, where research is discussed elsewhere (e.g., in academic papers) and where there is insufficient research. The questionnaire and workshop were used to help prioritise the research needs of the reservoir community.

The scoping study was undertaken concurrently with a number of other studies. By its very nature, research evolves with time. Although every effort was made to incorporate findings from other studies and research projects, inevitably the study can only reflect conclusions that were finalised at the time of writing.

1.2 Purpose

The purpose of the study is to identify further work that is required to understand the modes of failure of dams and how monitoring and measuring techniques can and should be used. The intention is that the findings, and any future research that ensues, will feed into a risk-assessment process. The overall objective is to carry out a scoping study that covers both topics, with the main objectives as described in Section 1.1.1 above.

A scoping study for a guide to risk assessment is being carried out separately and the report on risk assessment was taken into consideration in completing this report (see Section 2.1.1). Figure 1.1 is taken from the report and illustrates how the work on modes of failure of dams fits into the overall reservoir safety risk management process.

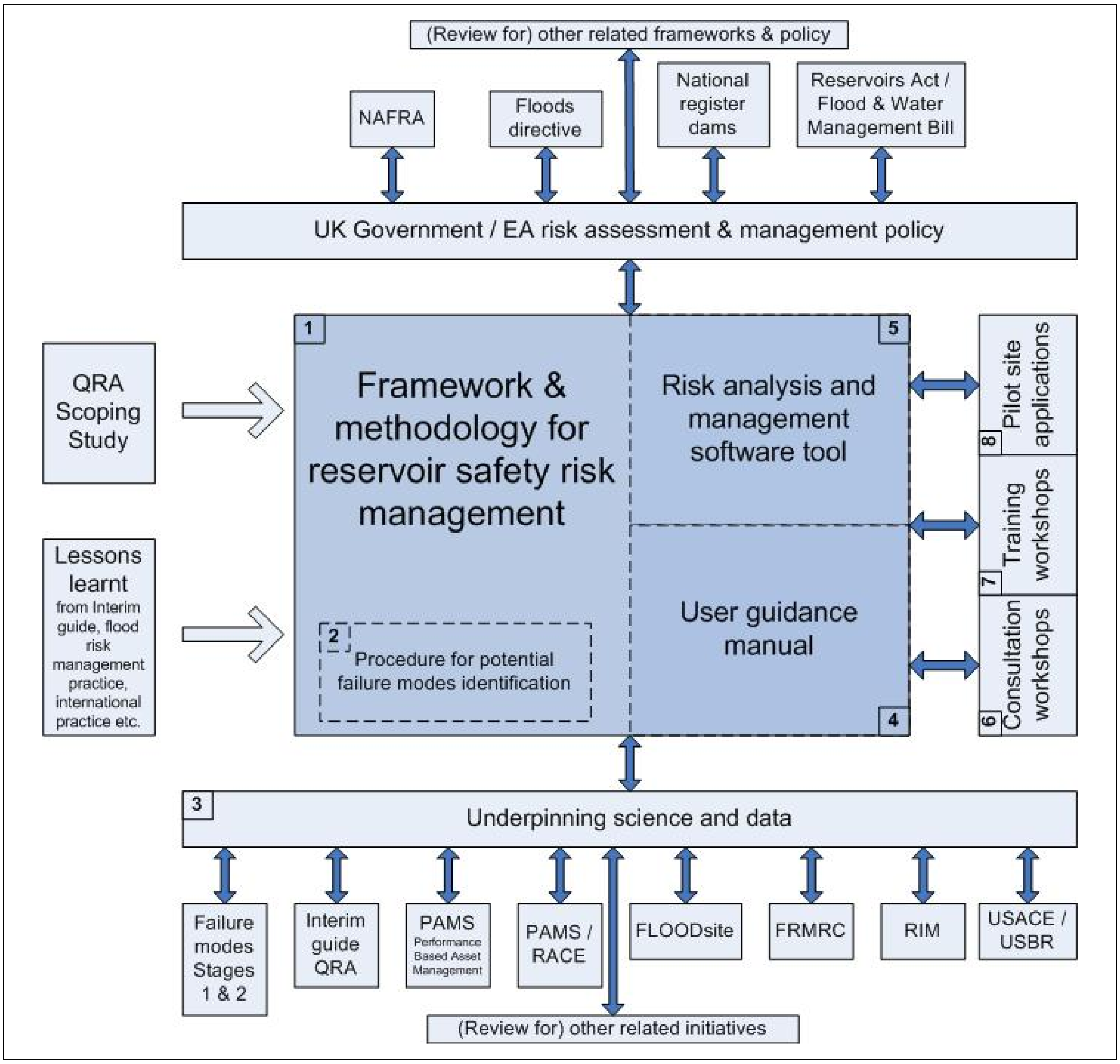

Figure 1.1 Overview of project links and outputs [taken from Environment Agency *Scoping Study for a Guide to Risk Assessment of Reservoirs*, Final Report SC070087].

The work on modes of failure and monitoring and measuring techniques is also relevant to a number of other initiatives recommended by the Defra R&D strategy. These are discussed further in Sections 3 and 4.

Clearly, the modes of failure of dams must be understood by the reservoir community, in particular linking the threats and hazards to the possible failure mechanisms that may result (see Section 2.2). The implications of observations made on site (e.g., by Supervising Engineers) must be understood fully. This scoping study is only part of a process of communicating to the reservoir community information on modes of failure and monitoring and measuring techniques. Ultimately an understanding of modes of failure should allow risk assessment studies to determine probabilities of occurrence of, consequence of and resilience to failure.

Common themes exist within some of the priority areas for research projects identified in the Defra Reservoir Safety Research and Development Strategy (FCERM, 2009). To identify further work on modes of failure of dams and monitoring and measuring techniques, reference is made to other areas within the strategy, which may provide the information required, either partially or in full. Some of the research identified within the strategy has commenced and results will be published in due course.

1.3 Definitions

A number of definitions are provided in the published literature. The following have been taken from Construction Industry Research and Information Association (CIRIA) report C542 *Risk Management for UK Reservoirs* (Hughes *et al*. 2000) and are considered to be the most appropriate for this study:

- **Failure (of a dam).** A major uncontrolled and unintended release of retained water, or an event whereby a dam is rendered unfit to safely retain water because of a total loss of structural integrity.
- **Hazard.** A situation with a potential for human injury, property damage or other undesirable outcome.
- **Risk.** A measure of the probability and severity of an adverse effect to life, health, property or the environment (ICOLD 2005). This is the definition used in the report *Scoping Study for a Guide to Risk Assessment of Reservoirs* (Atkins, 2009). In the scoping study, although a simple average measure of risk may be calculated by risk = probability times consequence, this definition has significant limitations when applied to the management of reservoir safety risks for events of low probability and high consequence.

The following terminology is used throughout this report:

The term monitoring and measuring techniques includes both equipment and its use, which may involve automatic or manual reading, and interpretation of results.

- **Threat.** An event or condition that may result in a hazard occurring. It is the threat that initiates a failure.
- M**ode of failure.** The mechanism by which a hazard leads to failure of a dam.

Although the above definitions are used for the purpose of this report, it will be necessary for the terminology in any new guidance to be consistent and a review may be required as part of the overall research strategy.

1.4 Key studies and documents

1.4.1 Defra Reservoir Safety Research and Development Strategy

Atkins, in collaboration with HR Wallingford, Bristol University and Chris Binnie Consulting, was commissioned by Defra to undertake work to determine future research needs with respect to reservoir safety in the UK and possible sources of funding. The main objectives of the projects were to:

- identify the issues that will impact reservoir safety in the future;
- identify sources of funding, including innovations to obtain funding for future research projects;
- provide a prioritised schedule of research projects for the planning period being considered.

The strategy follows on from the Water Act 2003, the Civil Contingencies Act 2004 and European Legislation (Directive 2000/60/EC; Directive 2007/60/EC). It identified 48 topics of research and ranked them according to priority, with possible sources of funding and estimated costs

Long-term drivers include climate change, ageing of dams, dam removal or discontinuance, sustainability and renewable energy, emergency preparedness and communication risks, and advances in the science of and developments in risk assessment, which includes the *Interim Guide to Quantitative Risk Assessment for UK Reservoirs* (QRA) by Brown and Gosden (2004b).

1.4.2 FLOODsite project

In April 2007, the Parliament and Council of the European Union agreed the wording for a new European Directive on the assessment and management of flood risks. The Integrated Project FLOODsite is listed as one of the European actions that support the Directive.

FLOODsite covers the physical, environmental, ecological and socioeconomic aspects of floods from rivers, estuaries and the sea. It considers flood risk as a combination of hazard sources, pathways and the consequences of flooding on the ‘receptors’ – people, property and the environment.

FLOODsite is an ‘Integrated Project’ in the Global Change and Ecosystems priority of the Sixth Framework Programme of the European Commission. It commenced in 2004 and continued until 2009. The FLOODsite consortium includes 37 of Europe’s leading institutes and universities, and the project involves managers, researchers and practitioners from a range of government, commercial and research organisations that specialise in aspects of flood risk management.

The FLOODsite project is broken down into seven distinct theme areas within which a total of 35 project ‘tasks’ are identified. The most relevant tasks to this report include Tasks 2, 4, 6 and 7, as these are closely interlinked with modes of failure of embankment dams.

Details of these tasks are available free of charge from the FLOODsite website, http://www.floodsite.net/html/work_programme1.asp.

1.4.3 CIRIA guides

CIRIA is a non-profit-distributing private sector organisation that carries out research and provides information for its members, who include types of organisations concerned with construction such as clients, professional practices, contractors, suppliers, educational and research establishments, professional institutions, trade associations, and central and local government.

The key CIRIA guides to this study include:

- CIRIA 116, *Design of reinforced grass waterways* (Hewlett *et al*., 1987);
- CIRIA 134, *Guide to analysis of open-channel spillway flows* (Ellis, 1989);
- CIRIA 148, *Engineering guide to the safety of concrete and masonry dam structures in the United Kingdom* (Kennard *et al*., 1996a);
- CIRIA 154, *Manual on the use of rock in coastal and shoreline engineering* (CIRIA, 1991);
- CIRIA 353 – Seawall design (Thomas and Hall, 1992);
- CIRIA 14, *Design of flood storage reservoirs* (CIRIA, 1996);
- CIRIA 161, *Small embankment reservoirs: a comprehensive guide to the planning design, construction and maintenance of small embankment reservoirs for water supply and amenity use* (Kennard *et al*., 1996b);
- CIRIA 170, *Valves, pipework and associated equipment in dams – guide to condition assessment* (Reader *et al*., 1997).

The CIRIA guides are currently available on-line and distributed in the CIRIA website, www.ciria.org.

1.4.4 BRE reports

The BRE Trust Companies include Building Research Establishment Limited and BRE Global Ltd, and are wholly owned subsidiary companies of the BRE Trust.

The key BRE reports to this study include:

- BR 210, *An engineering guide to seismic risk to dams in the United Kingdom* (Charles *et al*., 1991), along with *An application note to 'An engineering guide to seismic risk to dams in the United Kingdom*' (Institution of Civil Engineers, 1998);
- BR 303, *Investigating embankment dams: a guide to the identification and repair of defects* (Charles *et al*., 1996);
- BR 412 ,*Desiccation in clay soils* (BRE, 1996);
- BR 363, *An engineering guide to the safety of embankment dams in the United Kingdom* (Johnston *et al*., 1999).

The BRE reports are available on-line at the BRE bookshop website, www.brebookshop.com

1.4.5 Eurocodes

BSI British Standards has published a list of 57 structural design codes it plans to withdraw in March 2010. The majority have been superseded or made obsolescent by Eurocodes. The list includes all or most parts of well-known standards, such as;

- BS5400, Steel concrete and composite bridges;
- BS5628, Code of practice for use of masonry;

- BS5950, Structural use of steelwork in building;
- BS6399, Loading for buildings;
- BS8002, Code of practice for earth retaining structures;
- BS8004, Code of practice for foundations;
- BS8100, Lattice towers and masts;
- BS8110, Structural use of concrete.

BSI is obliged to withdraw all standards that have the same scope and field of application covered by the Eurocodes. Those partly covered by Eurocodes will be amended or revised to delete conflicting requirements and reflect the changed scope.

British standards are well understood by the reservoir community and are either referred to specifically in the key documents listed above, or have been used to adopt an appropriate methodology for analysis. Eurocodes differ in their approach, so work is required by the industry to understand the implications. This will affect both the design of new elements and the assessment of the integrity of an ageing infrastructure.

1.4.6 International Commission on Large Dams

The International Commission on Large Dams (ICOLD) is a non-governmental international organization that provides a forum for the exchange of knowledge and experience in dam engineering.

Its original aim was to encourage advances in the planning, design, construction, operation and maintenance of large dams and their associated civil works, by collecting and disseminating relevant information and by studying related technical questions.

Since the late 1960s, it has focused on subjects of current concern, such as dam safety, monitoring of performance, reanalysis of older dams and spillways, effects of ageing and environmental impact. More recently, new subjects include cost studies at the planning and construction stages, harnessing international rivers, information for the public at large and financing.

The published ICOLD bulletins key to this study include:

- ICOLD (1981), *The use of thin membranes on fill dams* (Bulletin 038)
- ICOLD (1982), *Bituminous cores for earth and rockfill dams* (Bulletin 042)
- ICOLD (1983a), *Deterioration of dams and reservoirs: Examples and their analysis*
- ICOLD (1984), *Lessons from dam incidents*
- ICOLD (1986b), *Materials for joints in concrete dams* (Bulletin 057)
- ICOLD (1987), *Spillways for dams* (Bulletin 058)
- ICOLD (1989a), *Monitoring of dams and their foundations – state of the art* (Bulletin 068)
- ICOLD (1989b), *Rockfill dams with concrete facing – state of the art* (Bulletin 070)
- ICOLD (1991), *Alkali–aggregate reaction in concrete dams – review and recommendations* (Bulletin 079)
- ICOLD (1992), *Spillways. Shockwaves and air entrainment – review and recommendations* (Bulletin 081)
- ICOLD (1993b), *Reinforced rockfill and reinforced fill for dams – state of the art* (Bulletin 089)
- ICOLD (1993c), *Embankment dams. upstream slope protection – review and recommendations* (Bulletin 091)
- ICOLD (1993d), *Rock materials for rockfill dams – review and recommendations* (Bulletin 092)

- ICOLD (1994), *Embankment dams – granular filters and drains* (Bulletin 095)
- ICOLD (2002), *Seismic design and evaluation of structures appurtenant to dams* (Bulletin 123)
- ICOLD (2005a), *Dam Foundations. Geologic considerations. Investigation Methods. Treatment. Monitoring* (Bulletin 129)

All the ICOLD bulletins are currently available on-line at http://www.icold-cigb.net

1.4.7 Flood Risk Management Research Consortium

The Flood Risk Management Research Consortium (FRMRC) project comprises two stages, the first of which was completed in 2004. It is sponsored by the Engineering and Physical Research Council under Grant EP/FO20511/1, with additional funding from the Environment Agency and Defra (Joint Defra–Environment Agency Flood and Coastal Erosion Management R&D Programme), the Northern Ireland Rivers Agency and the Office of Public Works, Dublin.

It was formulated to address key issues in flood science and engineering, and the portfolio of research includes the short-term delivery of tools and techniques to support more accurate flood forecasting and warning, improvements to infrastructure of flood management and reduction of flood risk to people, property and the environment.

A particular feature of the second phase is the concerted effort to focus on coastal and urban flooding. In addition, the consortium continues to provide internationally leading research in the area of land-use management in the context of the generation of floods during extreme rainfall.

There are some key flood embankment studies of relevance to this scoping study. One of these is Risk Assessment of Flood and Coastal Defence for Strategic Planning (RASP). To better understand the performance of flood and coastal defences it is often necessary to consider ‘systems’ of defences rather than single defences in isolation. At present there is limited guidance on assessing risk to large floodplain areas that depend on numerous, perhaps extensive and diverse, systems of defence, such as embankments, walls and moveable structures. The aim of RASP is to develop and demonstrate supporting methods to deal with such systems.

Another study is Performance-Based Asset Management Systems (PAMS), currently in Phase 2, which involves developing and demonstrating methodologies. To support management of the Environment Agency’s flood defences, PAMS will take a measured step forward in developing a performance-based approach to identify and prioritise works needed to manage existing flood defences. This approach will support the provision of improved inspection, operation, maintenance and management of flood defence systems through the identification of appropriate management interventions to reduce flood risk. The PAMS system will consider the whole life cycle of systems, as well as maintenance, renewal and replacement options.

Lessons can be learned from both RASP and PAMS for the management of reservoirs. However there are differences between flood defences, which are often long, linear assets with similar features, and dams, which may have unique characteristics.

1.4.8 Post-incident reporting for UK dams

The Environment Agency commenced annual post-incident reporting for UK dams in 2007. Three reports have been completed so far and the aim has been for the Environment Agency to work with the reservoir industry to put together a comprehensive database of incidents and near misses so that lessons can be learned and similar incidents avoided in the future. The reports are available on-line at http://www.environment-agency.gov.uk/business/sectors/102975.aspx

2 Framework for scoping study

2.1 Risk assessment

2.1.1 Scoping study for a guide to risk assessment

Definitions of different modes of dam failure must form a fundamental part of risk assessment for any dam or group of dams. A scoping study for a guide to risk assessment is currently being undertaken (Atkins, 2009). The study has identified the need not only to build on earlier work in the QRA (Brown and Gosden, 2004), but to integrate with government policy, other research initiatives and other risk-based strategies being worked on by others (e.g., flood and coastal erosion strategies). These have also been investigated as part of the study on modes of failure and monitoring and measuring techniques for this report. Although risk assessment is not within the scope of this report, an understanding of possible risk-assessment models is vital to the usefulness of this report and any future research projects it recommends. Indeed, this scoping study and work that follows from it will form part of the ‘underpinning science and data’ required for risk management of reservoir safety, as discussed in Final Report SC070087 (see Figure 1.1).

The interim guide to QRA provides a matrix in which the mechanisms of deterioration that link threats to failure modes are shown. This considers threats, both internal and external, to the reservoir and modes of failure of the dam that result from the threat. Risk is evaluated by multiplying the annual probability of failure (caused by the various possible threats) by the estimated costs associated with the consequences of an uncontrolled release of reservoir (likely loss of life, cost of damage, etc).

The scoping study for a guide to risk assessment (Atkins, 2009) discusses a number of possible frameworks in which to consider risk. A ‘source–pathway–receptor’ framework is suggested, whereby a sequence is put forward for modelling:

- sources (or initiating events);
- pathways (including system responses, outcomes and exposure factors);
- receptors (the impacts of consequences to receptors).

The source–pathway–receptor framework is reproduced in Figure 2.1.

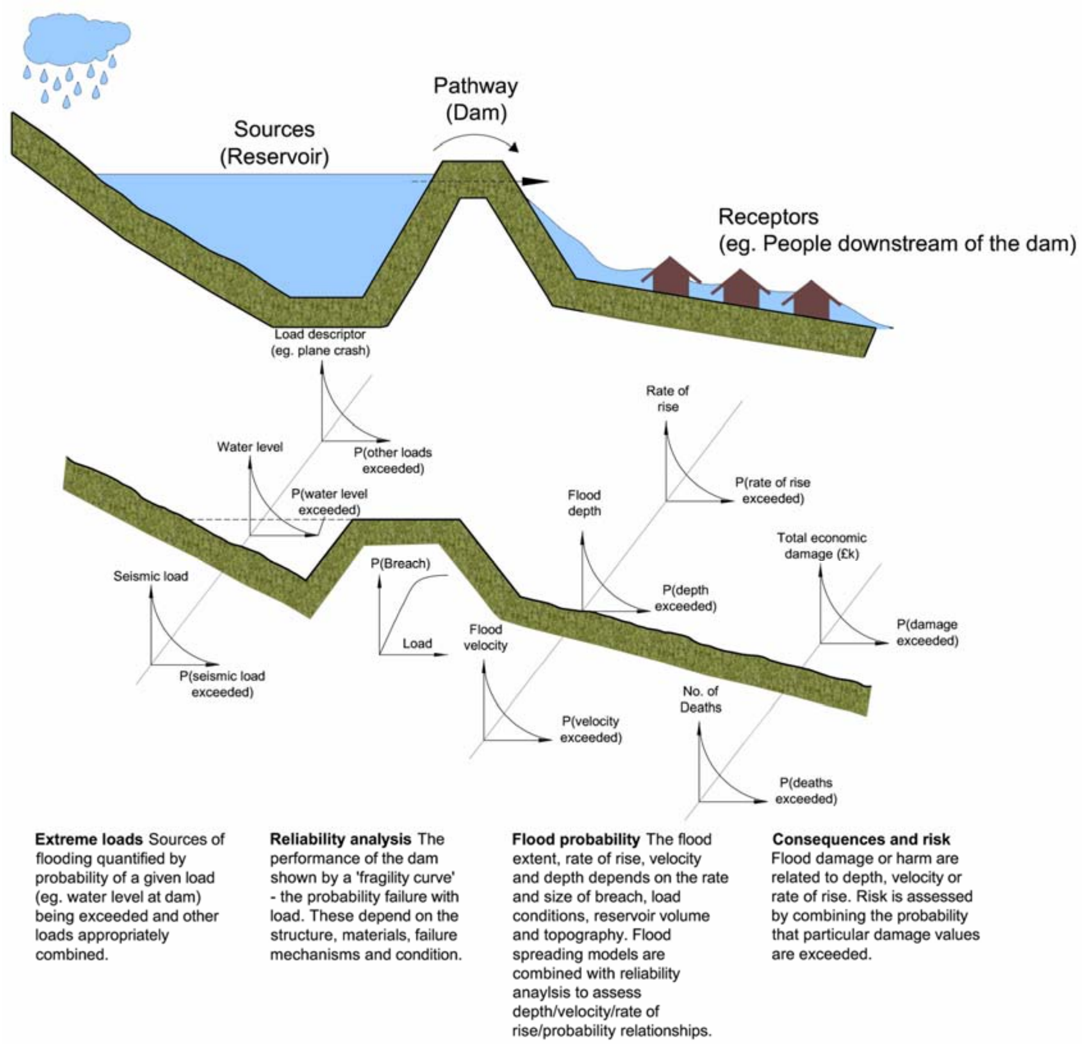

Figure 2.1 Source–pathway–receptor framework for the assessment of dams (Morris *et al*., 2009).

The source–pathway–receptor model is in line with work already underway on flood and coastal risk and is discussed in further detail in the Environment Agency guidance note known as Green Leaves 2 (Environment Agency, 2002). This note comments on the need to take account of both the probability of an event and the magnitude of the consequences of the event in risk assessment; both probability and consequence are outside the scope of this study, but must be considered in due course (see Section 6).

The importance of the consistency of risk-assessment methods is recognised, particularly when looking at the similarities between small embankment dams and flood embankments. However, it is also important to consider guidance produced by the wider reservoir community. Some background information is provided in Section 2.1.2 on the approaches used internationally.

2.1.2 International approach to the risk assessment of dams

2.1.2.1 International Commission on Large Dams

Risk analysis methods for dams are covered in ICOLD 130 (2005b), which is a consultative report and arguably puts forward the best international practice in dam engineering. Three approaches are considered:

- qualitative
- quantitative
- standard-based approach.

The qualitative approach comprises failure-modes analysis in which faults or initiating conditions are postulated and the analysis reveals the full range of effects on the system. This is 'failure modes and effects analysis' and can also take into consideration the probability and consequence of failure. The results are presented in a tabular form.

The quantitative approach is an 'event tree'[1] analysis, in which outcomes are identified, along with their probabilities, given the occurrence of an initiating event. A hazard leads to a subsystem response (including a fault tree analysis[2] and a reliability analysis) and this then leads to an estimation of risk, where probability and consequence are introduced.

In the standard-based approach risk analysis is not carried out explicitly, but is implied through the use of classification schemes according to a national or international standard. In the UK, reservoirs regulated under the provisions of the Reservoirs Act 1975 are categorised A to D (Institution of Civil Engineers, 1996). This categorisation is used to reflect the potential for loss of life and flood damage due to an uncontrolled release of the reservoirs.

2.1.2.2 Federal Energy Regulatory Commission dam safety assessments

In the United States, 'failure mode analyses' are now a routine part of dam safety assessments, which are required by the Federal Energy Regulatory Commission (FERC). It has been recognised that potential failure modes require assessment, but not all modes can be the subject of deterministic analysis. Since 2002, potential failure mode analyses (PFMAs) have been carried out for all high and significant downstream hazard-potential dams that require inspections. These are conducted by reviewing the available information on the dam and then analysing the ways in which the dam could potentially fail through a facilitated discussion among representatives of the owner, including their consultant(s) if applicable, and the FERC inspector. This has improved the understanding of the design and construction, project history, operation and maintenance, surveillance and monitoring of dams, and how these may influence potential failure modes for a particular structure.

In the spring of 2008, FERC proposed to extend the PFMA process to significant hazard-potential dams that do not require regulation under Part 12D of FERC's Safety

[1]An event tree is a method to assess risk, whereby an initiating event may lead to a number of different outcomes, each of which in turn leads to further potential outcomes. Individual probability values are assigned to each 'branch' that links events to outcomes, which thus enables probability of the final outcome to be calculated.
[2]A fault tree is essentially the opposite of an event tree, in that the starting point is a fault, in this case failure of a dam, and the branches from the fault are all potential mechanisms that could have led to the fault developing.

of Water Power Projects and Project Works regulations and low hazard-potential dams greater than 9 feet (2.7m) high or that impound more than 25 acre-feet (approximately 31,000 m^3).

2.1.3 Scoping study approach

For this scoping study a simple model has been adopted, which is able to fit into any of the above models for risk assessment. A 'threat', as defined in Section 1.3, is the first point on an event tree and could, alternatively, be called an initiating event or 'source' of a failure. From the threat a 'hazard' may result. For example, the threat of extreme rainfall and/or snow and the resulting flood may lead to the spillway capacity being exceeded, and thus a 'hazard' is formed. This 'hazard' may or may not then lead to the development of a 'mode of failure' that results in failure of the dam. In this example, if the embankment eroded because the spillway capacity was exceeded, the 'mode of failure' would be dam breach. Further details on the relationships between the threats, hazards and modes of failure are provided in Section 2.2.

Importantly, a number of hazards may combine to cause failure of a dam and some will be more severe and/or have a higher probability of occurrence than others. Ultimately, if this study feeds into a risk assessment, as it is hoped, the grouping of hazards will need to be considered, as will the relative contribution of each hazard. The use of event trees and fault trees should be considered, but is outside the scope of this report.

At the time of writing, it is understood that some preference has been given to the source–pathway–receptor model (Section 2.1.1). In this model the threat may be the source of failure, the pathway comprises not only the dam, but also its environs, and the receptor is the population and infrastructure downstream of the reservoir. The receptor is not considered within this scoping study, but it must be considered in future work and will be very site-specific. The impact of flooding on people, businesses and services is at the heart of government policy, along with the manner in which incidents are dealt with, and these issues are highlighted in a review by Sir Michael Pitt, written after the floods of summer 2007 (Pitt, 2008).

2.2 Threats, hazards and modes of failure

2.2.1 Threats (initiating events)

The following threats have been identified through a literature search and by consultation:

- ageing
- aircraft strike
- animal activity
- changes in groundwater flow/chemistry
- earthquake
- extreme rainfall/snow flood
- failure of nearby infrastructure
- failure of reservoir in cascade upstream
- human activity
- ice/frost
- layout, design or construction inadequate or inappropriate
- mal-operation
- mining/ mineral extraction
- sunlight
- terrorism/sabotage/accident
- water loading
- wind

Many of the dams and reservoirs in England and Wales are historic structures that have experienced a number of environmental and other changes in their lifetimes. To continue to provide a resilient infrastructure, the potential for future changes in climate, environment and economy must be taken into consideration. The significance of individual threats listed above may change over time.

2.2.2 Hazards

The threats identified in Section 2.2.1 may lead to the development of one or more hazards, as listed in Table A.1 (Appendix A).

2.2.3 Modes of failure

A number of modes of failure defined from the literature review and consultation process are listed in Table A.2. There are relatively few modes of failure, with the main concerns in England and Wales arguably being overtopping and dam breach (of embankment dams). The modes of failure have not been categorised, for example into 'internal' or 'external', because of the different procedures in the literature, and instead are listed alphabetically.

As discussed in Section 2.1.3, a number of hazards may combine to cause failure of a dam. The combination of hazards to cause any one of these modes of failure requires further work (see Section 6), but brief descriptions of the modes of failure identified are given in Section 3.2.

2.3 Monitoring and measuring techniques

2.3.1 Indicators

According to the principles set out in Section 2.2, a dam can only fail if a hazard occurs. If it is possible to monitor or measure the hazards that may have an impact on any particular dam, then in theory it is possible to identify a potential failure in advance of that failure occurring. A number of indicators in different locations within an embankment dam could be used to determine whether or not a hazard, and potentially a mode of failure, is developing. However, research undertaken as part of this scoping study revealed that what is actually being measured on dams is not understood clearly. Consideration of what indicators there are for each of the hazards should be made in future studies (see Section 6). A framework is provided Table A.3.

2.3.2 Monitoring and measuring techniques

The techniques that can be used to check for the indicators defined in Table A.3 were considered in this scoping study and are discussed in Section 4.

Embankment deformation, pore pressure and seepage rate are probably the most helpful indicators. Recently, such techniques have been used, with some success, to determine location of leakage.

3 Modes of failure of dams

3.1 Hazards

3.1.1 Differential settlement or deformation

Definition

Differential settlement can be caused by:

- foundation settlement;
- unequal layers of compressible strata in the foundation;
- changes in height and composition of embankment;
- inclusion of incompressible structures such as culverts within embankments;
- the interface between compressible fill and rigid structures.

Differential settlement has the potential to cause hydraulic fracture or the development of seepage paths.

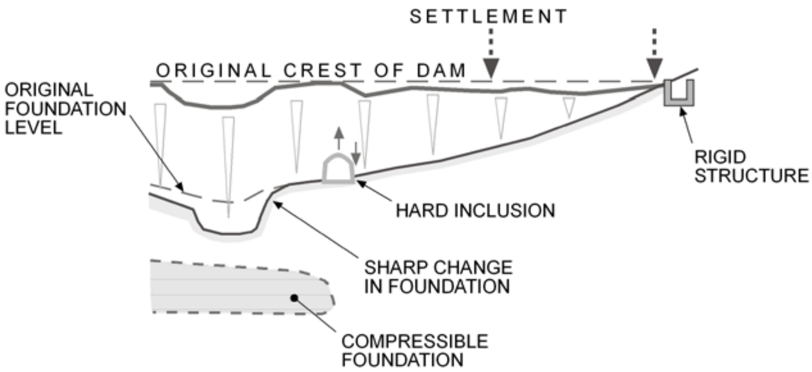

Figure 3.1 Possible mechanisms of differential settlement in a dam.

Guidance on differential settlement or deformation is provided in BR 363 and BR 303. Settlement as a result of foundation problems can be found in ICOLD (1989a, 1993a, 2005a) and relevant papers are described in Section 3.1.5. In addition, deformations within the dam embankment are reviewed by Penman and Charles (1973, 1985), Flemming and Rossington (1985), Tedd *et al*. (1995, 1997a., 2002), Nilsson and Norstedt (1991), Holton (1992) and Hunter and Fell (2003). A general review of safety research in old embankment dams is given in Charles and Wright (1993). Case studies are reviewed in Tedd *et al*. (1988, 1990) and Environmental Agency *Post-incident report*s (2008, 2009). Studies on earthquake-induced deformations include Makdisi and Seed (1978) and Swaisgood (1995, 1998).

The Environment Agency's database of serious dam incidents lists case studies on differential settlement or deformation of embankment dams.

Although this subject was not highlighted in the questionnaire as one that required further guidance, the workshop concluded that guidance on differential settlement needs to be re-issued.

Differential settlement is not mentioned in the Defra strategy.

Re-issuing of current guidance on differential settlement or deformation is needed. This is a general comment that relates to some of the existing key guidance documents.

3.1.2 Rapid drawdown

> **Definition**
>
> Lowering the water level in a reservoir faster than the pore pressures can dissipate from the upstream shoulder of an embankment dam.
> This can lead to slope instability and slumping of material underwater, potentially blocking outlets.

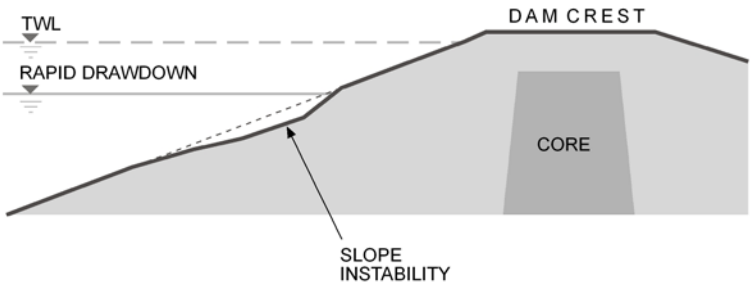

Figure 3.2 Effect of rapid drawdown [TWL, top water level (normally used to mean the overflow weir level in the reservoir)].

Guidance on rapid drawdown is provided in BR 363. Additional references identified include Paton and Semple (1960), Binnie *et al*. (1992) and Kovacevic *et al*. (1997). Soil mechanics text books, such as Craig (2004), discuss rapid drawdown in relation to slope stability. Case studies include Fort Henry embankment (Long *et al*., 2002), Teesdale dams (Prentice, 2003) and Sutton Bingham dam discussed in the latest BDS conference by Welbank *et al*. (2008).

The Environment Agency's database of serious dam incidents lists case studies that involve rapid drawdown.

The workshop highlighted that rapid drawdown depends mainly on the permeability of dam materials and as such can be quite site-specific, and requires specialist advice from a geotechnical engineer. There was some discussion on the need to clarify acceptable rates of drawdown. The questionnaire did not highlight the subject as one that required further guidance.

Rapid drawdown is not mentioned in the Defra strategy.

Further guidance on acceptable rates of drawdown may be required in the future, but this is not considered to be a high priority.

3.1.3 Reduced freeboard

Definition

The dam freeboard is the vertical height from top water level to the top of the dam (Institution of Civil Engineers, 1996).

Reduced freeboard can result in wave overtopping or wave slop. It can result from:

- settlement
- internal erosion

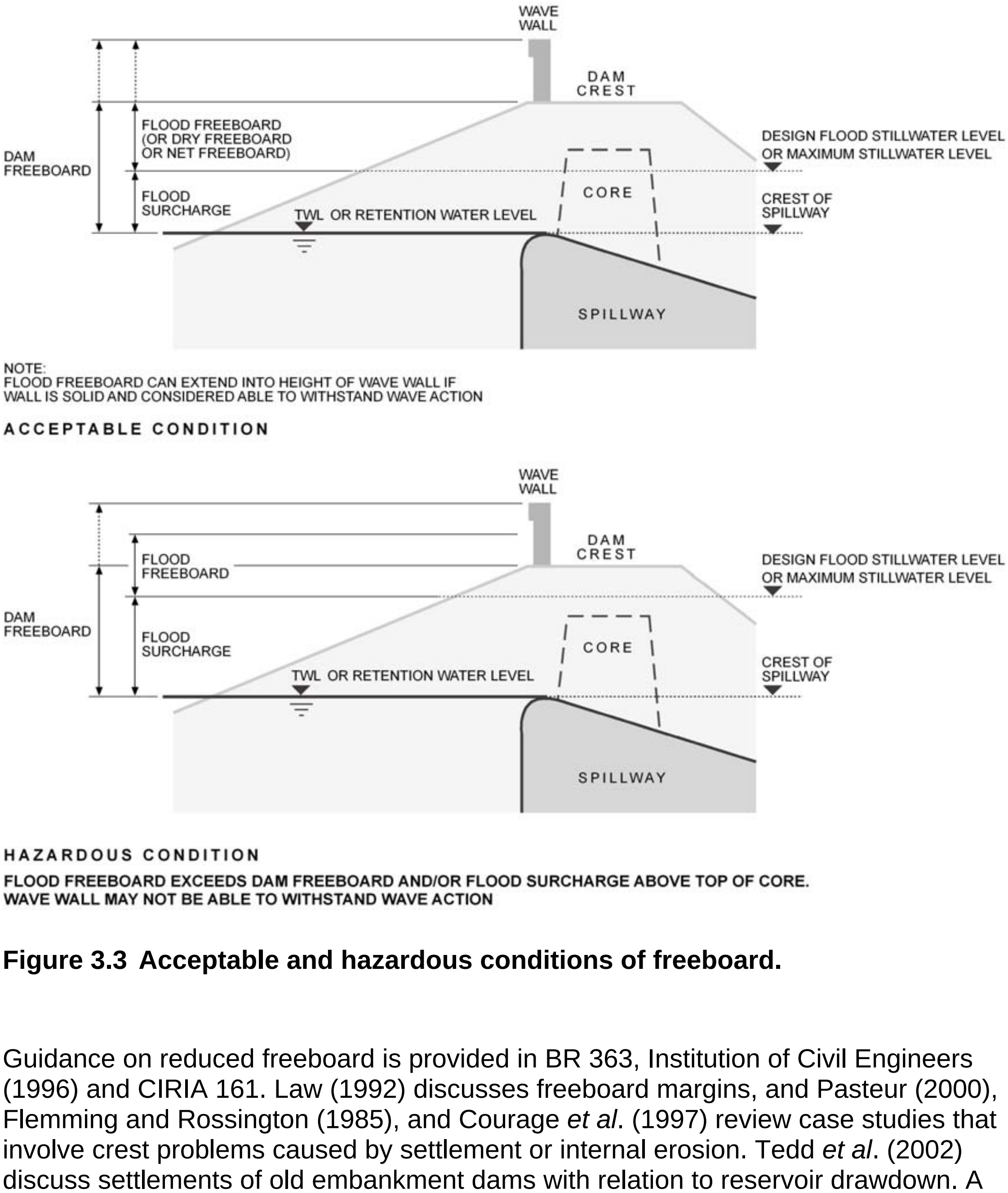

Figure 3.3 Acceptable and hazardous conditions of freeboard.

Guidance on reduced freeboard is provided in BR 363, Institution of Civil Engineers (1996) and CIRIA 161. Law (1992) discusses freeboard margins, and Pasteur (2000), Flemming and Rossington (1985), and Courage *et al*. (1997) review case studies that involve crest problems caused by settlement or internal erosion. Tedd *et al*. (2002) discuss settlements of old embankment dams with relation to reservoir drawdown. A case study that involved deformation of the crest, resulting in reduced freeboard, is Sutton Bingham dam, as described in the Environment Agency *Post-incident report* (2009).

Research on flood levels that eventually result in reduced freeboard and overtopping is one of the key subjects investigated within FLOODsite or FRMRC and reference should be made to published documents such as FLOODsite (Task 1 and Task 2) or

FRMRC RPA3 – Real-TIME Flood Forcasting found on http://www.floodrisk.org.uk/index.php?option=com_content&view=article&id=105&catid=0&Itemid=50.

The hazard of reduced freeboard is normally associated with other hazards, which involve settlement or internal erosion and, as such, reference should be made to the hazards in Sections 3.1.4–3.1.11.

The workshop highlighted that modes of failure associated with reduced freeboard can happen overnight as a result of human intervention. Other issues highlighted include toppling vegetation and crest issues in general. This hazard was not mentioned in the questionnaire.

Reduced freeboard is not mentioned explicitly in Defra's research strategy, but it does relate to other hazards and threats that are mentioned and ranked with high priority.

Research on freeboard itself is not required. However, research on some of the other hazards which lead to this condition will also assist in understanding the hazard of reduced freeboard.

3.1.4 Settlement (consolidation) of embankment

Definition

Consolidation is the process of volume reduction that occurs when compressive stresses are applied to soil.
Primary consolidation results from the dissipation of excess pore pressures into steady seepage values, generally after construction or raising of the dam.
Secondary consolidation in clay cores and foundations may continue even when excess pore pressure has dissipated.
The amount of settlement is proportional to the height of the dam and is influenced by several factors:

- In high-plasticity clays, such as London Clay, a seasonal swelling and shrinkage can affect near-surface measurements.
- Collapse compression of rockfill in shoulder material on first wetting.
- Embankments deform under changes in water level. The magnitude of the settlement of clay-core dams depends on the depth and duration of drawdown and the height of the dam. The pattern of settlement for dams with upstream membranes is different.

Settlement not explained by these factors may be the result of problems such as internal erosion.
Settlement may result in reduced freeboard.

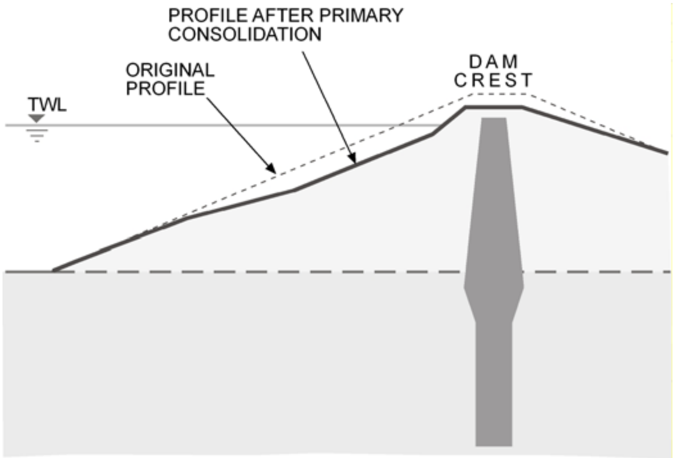

Figure 3.4 Primary consolidation.

Comprehensive guidance on consolidation of embankments is given in BR 363 and BR 303. Additional references include those described in Section 3.1.5, with additional papers such as Tedd *et. al* (2002), Kovacevic *et al*. (1997), Tedd *et al*. (1994, 1997b, 2002). Case studies include: a review of settlement predictions at Ladybower dam (Vaughan *et al*., 2000),and a review of observed and predicted settlements in large dams by Penman *et al*. (1971).

The workshop highlighted problems associated with unsaturated soils and an emphasis was placed on the need to be aware of this hazard and the available guidance mentioned above. The questionnaire gave no indication of missing guidance on this topic.

The hazard of settlement of embankments is not mentioned explicitly in Defra's research strategy.

No further guidance on consolidation of embankment is deemed necessary. Further research on unsaturated soils is underway in geotechnical academic institutions.

3.1.5 Settlement of foundation

Definition

The foundation of the dam or reservoir settles as a result of mining, oil or gas extraction. This can result in:

- opening of joints in the foundation, which creates seepage paths;
- damage to cut-offs, which creates seepage paths;
- changes in relative levels of dams and appurtenant structures that cause them not to operate as designed;
- differential settlement if the mining extraction is uneven or protection pillars are not large enough.

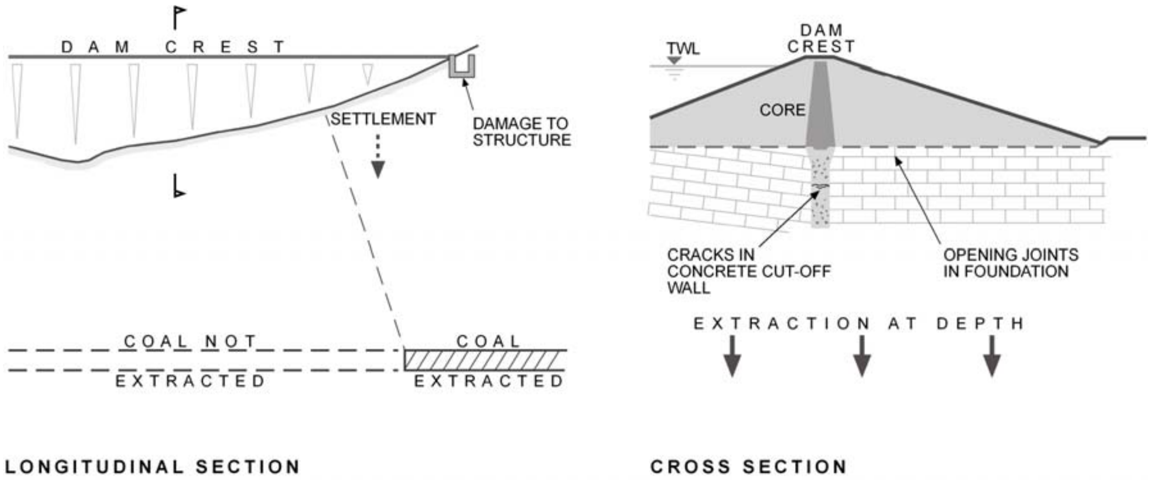

Figure 3.5 Foundation settlement.

Guidance on settlement of dam foundations can be found in BR 363 and ICOLD (1989a, 1993a, 2005a), and additional papers of note include Charles (1993), Grundy (1955), Henkel *et al*. (1964), Keefe and Dick (1958), Lowe-Brown (1940, 1948) and Tedd *et al.* (1997a). Case studies that refer to mining subsidence include Ferguson and McFadyean (1994), Hughes and Beech (1998), Hughes (1998), Long and Scott (1998), and McLellan (1955).

The Environment Agency's database of serious dam incidents lists those that involve settlement of the foundations.

As this hazard is related to other hazards that involve internal erosion and deterioration of foundation-soil strength, Sections 3.1.8, 3.1.9, 3.1.27 and 3.1.28 should also be referred to.

The workshop highlighted the importance of cyclic loading, but the hazard was concluded to have sufficient guidance. This conclusion is supported by the questionnaire, in which this hazard was not mentioned. However, some reference was made to geotechnical modes of failure as a whole.

The hazard of settlement in the foundation is not mentioned explicitly in Defra's research strategy. However, research into the related subject of internal erosion is ranked number 1.

No further guidance on foundation settlement is deemed necessary at this stage.

3.1.6 Seepage

Definition

Steady passage of water through, underneath or around a dam. Seepage can cause internal erosion.

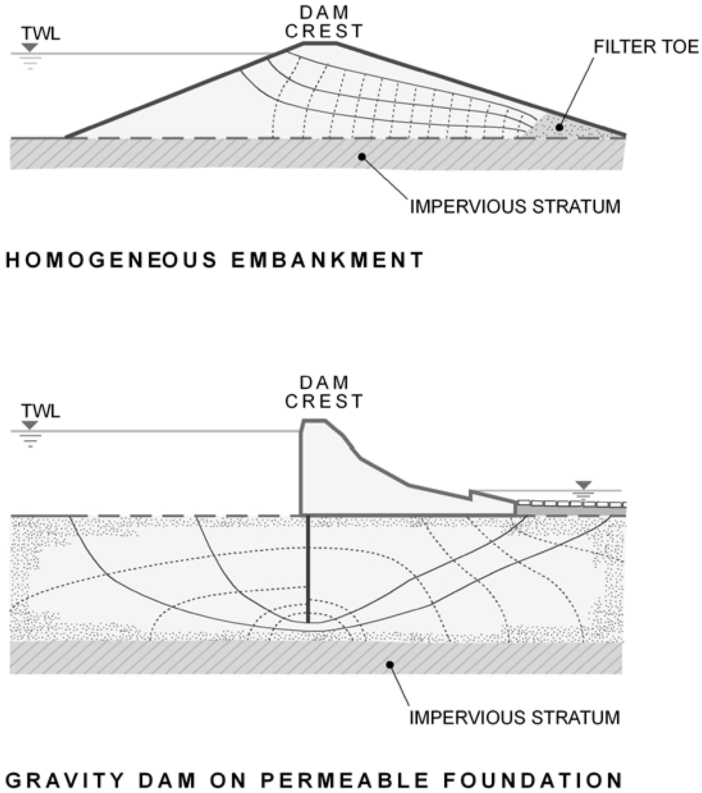

Figure 3.6 Seepage.

Seepage is discussed adequately in BR 303, BR 363, CIRIA 161, ICOLD (1994), Environment Agency incident report (2009) and in several key papers such as Brown and Gosden (2000), Brown and Bridle (2005), Tedd *et al*. (1987), Penman *et al*. (2000) and Vaughan (1989).

One of the key concerns about seepage is the internal erosion that may result. Internal erosion has been the focus of much attention in recent years and many relevant academic papers are published. Particular reference is given to the papers submitted for the 15th BDS Biennial Conference in 2008 (see below). Recently, Defra (2008) issued a report named *Layman's Guide to Internal Erosion* (Rev. 1.02), which explains the hazard to dam owners. Two key guides with regards to early detection and real-time monitoring of internal erosion were issued by Jacobs (2007).

Case studies that involve seepage problems include Rotton Park (Andrews and Dornstadter, 2000), March Haigh (Beaver, 1999) and Winscar (Carter *et al*., 2000) dams. This issue was also discussed at the recent BDS conference and information is given in papers by Bridle (2008), Brown and Bridle (2008) and a case study that involves Torside reservoir by Kofoed *et al*. (2008). Research is currently underway at Imperial College on internal erosion and seepage, which involves discrete element modelling (DEM) of the 'sanding' process.

Seepage through sandy cores was studied in FLOODsite Task 4 (2007) and reliability equations are available.

As this hazard is closely related to those that involve internal erosion and piping, reference should be made to Sections 3.1.7–3.1.11.

The Environment Agency's database of serious dam incidents lists case studies that involve seepage.

The workshop and questionnaire highlighted this hazard as one that requires further research, particularly with respect to the hazard of internal erosion.

The hazard of seepage is not mentioned explicitly in Defra's research strategy. However, research on the general subject of internal erosion is ranked number 1.

The hazard of seepage requires further research. However, research regarding the hazard of internal erosion is already underway and any further research on seepage is therefore not considered to be a high priority.

3.1.7 Concentrated erosion

Definition

In soils that are capable of sustaining an open crack, or in the interconnecting voids in a continuous permeable zone, erosion occurs along the sides of the crack (or voids) where the shear stress exceeds the critical value, but at low flows there may be leakage with no erosion (Brown and Bridle, 2008).
Concentrated erosion can also take place alongside structures such as culverts or spillway walls.

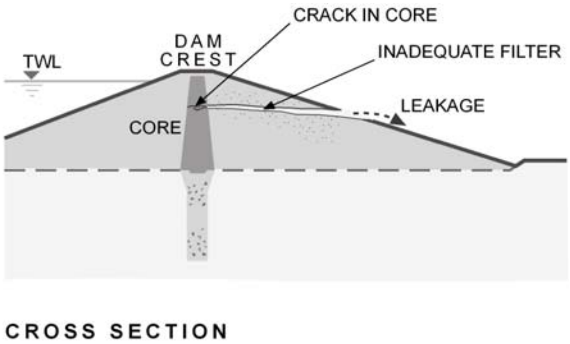

Figure 3.7 Concentrated erosion.

Concentrated erosion constitutes a specific form of internal erosion in dams and, as such, the reader is referred to the literature reviews in Sections 3.1.6 and 3.1.8–3.1.11. Resistance of clay cores to erosion is given in Atkinson *et al*. (1989).

The Environment Agency's database of serious dam incidents lists case studies that involve concentrated erosion.

The workshop highlighted references such as the ICOLD Internal Erosion Working Party and recent research carried out by the Corps of Engineers and Bureau of Reclamation in the USA, and also in Holland. The workshop and questionnaire highlighted this hazard as requiring significant further research.

The hazard of concentrated erosion is not mentioned explicitly in Defra's research strategy. However, research on the general subject of internal erosion is ranked number 1.

The hazard of concentrated erosion requires further research. However, research on the general hazard of internal erosion is already underway and further research is therefore not considered to be a high priority.

3.1.8 Backward erosion (piping)

Definition

For erosion that starts at the exit point, backward erosion develops a continuous passage when the seepage gradient exceeds the 'flotation gradient' of the soil (Brown and Bridle, 2008).

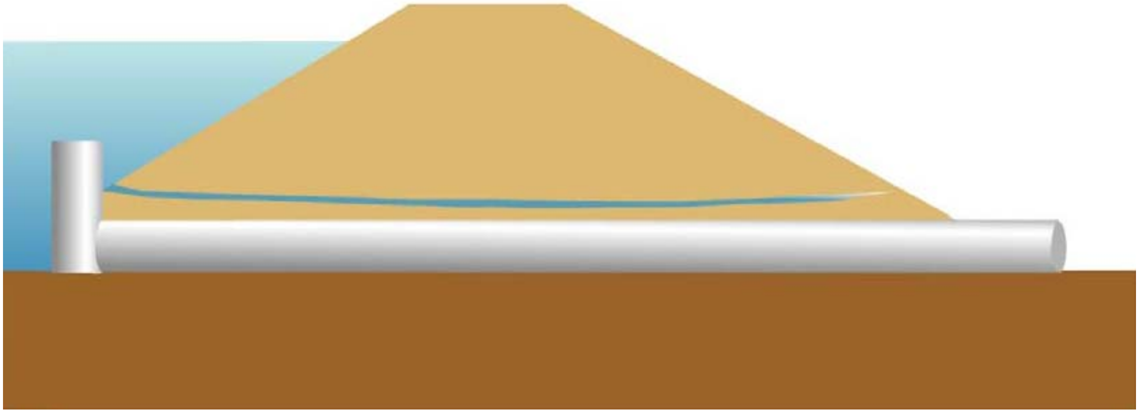

Figure 3.8 Backward erosion (Prinsco, 2009).

Backward erosion constitutes a specific form of internal erosion in dams and, as such, the reader is referred to the literature reviews in Sections 3.1.6, 3.1.7 and 3.1.9–3.1.11.

Additional references that deal directly with the problem of piping include Dise (1998), Foster *et al*. (1998b, 2000), Fell *et al*. (2004), Foster and Fell (2000), Myogahara *et al*. (1993), Van Nnortwijk *et al*. (1999), Weijers and Sellmeijer (1993), Luehring *et al*. (1999), Wan *et al*. (2002) and Wan and Fell (2002). Several dam incidents are given in the Environment Agency *Post-incident report*s (2008, 2009) and in Foster *et al*. (1998a). A key reference for the mechanism of piping in sandy gravels is Skempton and Brogan (1994). Piping is also studied in FLOODsite (Task 4) and reliability equations are available.

The hazard of backward erosion is not mentioned explicitly in Defra's research strategy. However, research on the general subject of internal erosion is ranked number 1.

The hazard of backward erosion requires further research. However, research on the general hazard of internal erosion is already underway and further research is therefore not considered to be a high priority.

3.1.9 Contact erosion

Definition

Erosion at the horizontal boundary of a fine soil overlying a coarse soil where the fine soil is washed into the coarse soil by horizontal flow (Brown and Bridle, 2008). Contact erosion may also occur at the horizontal boundary of a fine soil when it overlays a fractured foundation and is washed into rock fissures by horizontal flow.

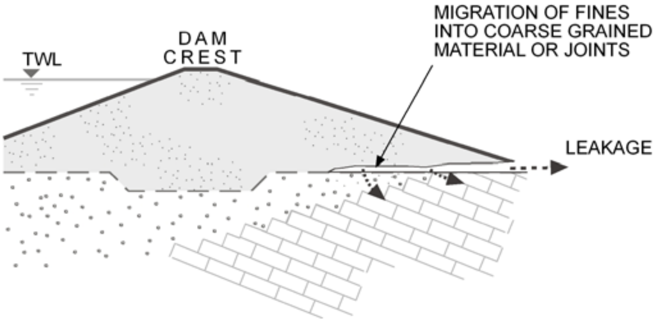

Figure 3.9 Backward erosion.

Contact erosion constitutes a specific form of internal erosion in dams and, as such, the reader is referred to the literature reviews in Sections 3.1.6–3.1.8, and 3.1.10 and 3.1.11.

The workshop highlighted erodibility of different geologies and the site-specific nature of this hazard.

The hazard of contact erosion is not mentioned explicitly in Defra's research strategy. However, research on the general subject of internal erosion is ranked number 1.

The hazard of contact erosion requires further research. However, research on the general hazard of internal erosion is already underway and further research is therefore not considered to be a high priority.

3.1.10 Internal erosion along an appurtenant structure

Definition
Erosion at the boundary between the soil and an appurtenant structure.

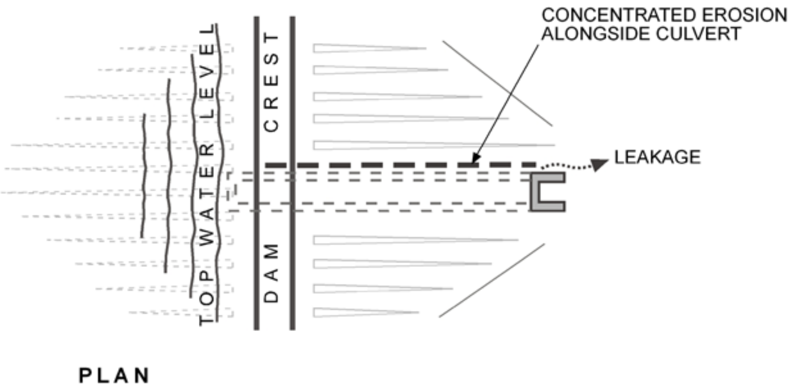

Figure 3.10 Erosion between the soil and an appurtenant structure.

nternal erosion along ancillary structures is closely related to internal erosion in dams and, as such, the reader is referred to the literature reviews in Sections 3.1.6–3.1.9 and 3.1.11.

A case study that involves failure along an outlet pipe in Warmwithens dam is given in Wickham (1992).

The Environment Agency's database of serious dam incidents lists case studies that involve internal erosion along ancillary structures.

The hazard of internal erosion along ancillary structures is not mentioned explicitly in Defra's research strategy. However, research on the general subject of internal erosion is ranked number 1.

The hazard of internal erosion along ancillary structures requires further research. However, research on the general hazard of internal erosion is already underway and further research is therefore not considered to be a high priority.

3.1.11 Suffosion

Definition

Mass erosion in soils that are internally unstable. Fines transported by seepage flow between the larger soil particles (Brown and Bridle, 2008).
The eroded material may be washed out of the downstream dam face or into the foundations, particularly where the foundations comprise fractured material.

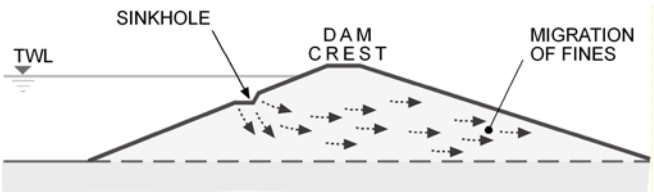

Figure 3.11 Mass erosion in soils that are internally unstable.

Some guidance on the hazard of suffosion is given in BR 363 and BR 303, and some reference to the process when it occurs within the foundations is given in ICOLD (1993a). Academic papers identified include Burenkova (1993), Wan and Fell (2003) and a key paper by Schwab (1993). Several papers were published recently on internal erosion, including the hazard of suffosion in the BDS 15th Biennial Conference by Bridle (2008) and Brown and Bridle (2008). In addition, papers by Kofoed *et al*. (2008), who investigated Torside Reservoir, and Rönnqvist (2008) discuss recent methods for the detection of internal erosion and leakage within embankment dams such as Torside Reservoir.

Other key papers on internal erosion include Atkinson *et al*. (1989), Tedd *et al*. (1987), Charles (1993, 1998, 2001, 2002), Charles *et al*. (1995), Burns (2004), Brown and Bridle (2005), Brown and Gosden (2004a), Vaughan (2000), Dornstadter (1997), Chapuis (1992) and Stewart *et al*. (2005). Case studies that involve some form of internal erosion are given in the Environment Agency's *Post-incident report*s (2008, 2009) and a review of remedial work to clay cores that have suffered from internal erosion is given in Tedd *et al*. (1994).

Several other case studies include Walshaw Dean Upper dam (Robertshaw *et al*., 1998) and Brent Dam (Tedd *et al*., 1998b), and case histories that involve small dams are given in Hinks and Williams (2004). Johansen *et al*. (1997) and Norstedt and Nilsson (1997) review internal erosion in Swedish dams. A case study that involved Winscar reservoir is discussed in Carter *et al*. (2002a,; 2002b). Guidance regarding filter design is given in BR 363, CIRIA 161, Vaughan (1982) and Vaughan and Bridle (2004).

Internal erosion with particular reference to suffosion and filter stability was studied in the FLOODsite (Task 4) project and reliability equations are available.

The hazard of suffosion is not mentioned explicitly in Defra's research strategy. However, research on the general subject of internal erosion is ranked number 1.

The hazard of suffosion requires further research. However, research on the general hazard of internal erosion is already underway and further research is therefore not considered to be a high priority.

3.1.12 Problematic embankment fill material (for example, peat)

Definition
Some old flood embankments or small embankment dams may have been constructed from materials such as peat or heterogeneous and/or poor-quality fill. This can leads to problems such as instability and differential or excessive settlement.

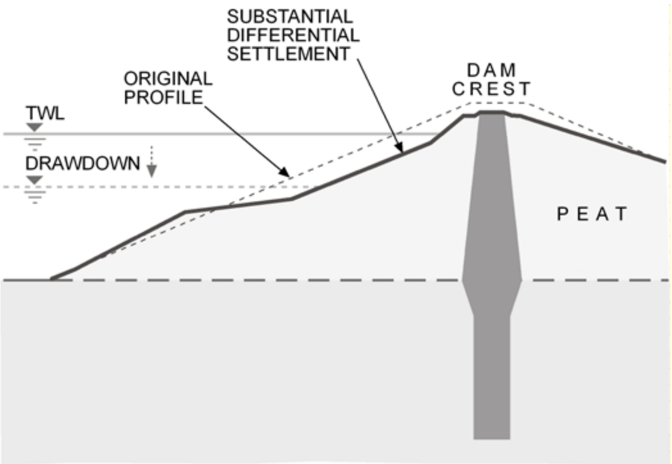

Figure 3.12 Problematic embankment fill material.

The hazard of dams made of problematic fill material, such as peat, was raised in the workshop as a hazard to be considered. No existing guidance was identified on this hazard, and this issue was not raised in the questionnaire.

The hazard of problematic fill material is not mentioned explicitly in Defra's research strategy.

It is concluded that the hazard of problematic fill material should be considered for further research, but that it is mainly a site-specific issue which requires the attention of the owner or inspecting engineer. This hazard could be considered further if any of the key references are updated prior to re-issue.

3.1.13 Animal activity

Definition
Problems arise with the management of animals who regularly inhabit earth embankments and create burrows or tracks that affect the structure. Burrows within the embankment can cause weakness, increase hydraulic gradients and, in extreme cases, form holes through the dam. Tracks or scrapes on the surface can encourage infiltration of rainwater. Animal activity can also result in failure of bywash channels.

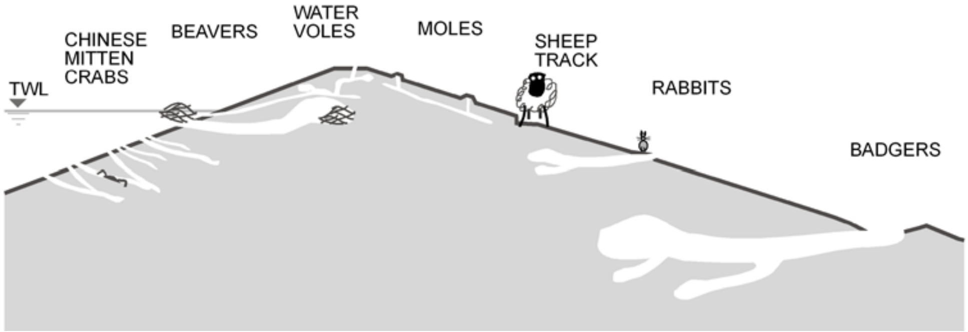

Figure 3.13 Pattern of animal activity.

Problems associated with the management of animal activity are discussed in CIRIA 161 and BR 363 with relation to embankments. Roper (1992) discusses badgers in great detail and provides valuable information on their behaviour. The recent Environment Agency *Post-incident report* (2009) discusses a case study that involved a small embankment reservoir in which seepage was induced by animal burrowing, and emphasises the importance of checking for animal infestation. It is understood that a post-incident bulletin is currently being drafted on animal activity.

Academic papers identified include a case study in the UK (Fletcher *et al*. 1997). A number of papers that included information on this topic were also presented at the 2008 United States Society of Dams conference. In-depth knowledge is usually provided by specialist organisations and it is possible that an addendum to existing guides could be used to place more emphasis on the subject. The subject was not highlighted to require further guidance in the questionnaire.

The workshop highlighted the need to assimilate knowledge from the ecological community and conflicts with asset managers. In particular, it is imperative that timely advice is sought on the requirements of regulatory bodies, such as Natural England. It was noted that there is no simple answer because of sometimes conflicting legislation and that the problems are of a site-specific nature.

Comments from senior members of the reservoir community recommended that the research conducted in the USA, especially at the United States Society for Dams, will be of relevance to future studies. It was thought that the FLOODsite project had dealt with the risk from animal holes on embankment failure, although this was not identified in the review of the different Tasks.

The hazard of animal activity is not mentioned explicitly in Defra's research strategy.

Guidance on the management of animal activity is required and should be collated from existing knowledge within the ecological community. Guidance should also be sought on the processes of both initial animal activity and subsequent behaviour of structures and water flow. The guidance should take into consideration findings of recent international research.

3.1.14 Vegetation

Definition

Vegetation growing on the upstream face or on the crest can damage wave protection or penetrate waterproof membranes.
Trees or other deep-rooted plants grow on the downstream face of the embankment. The roots can penetrate the core and cause flow concentration if the crest is overtopped. Falling trees can cause damage; rotting roots and stumps can leave voids.
Other vegetation on the downstream face, if not maintained, can obscure inspection and promote animal infestation.

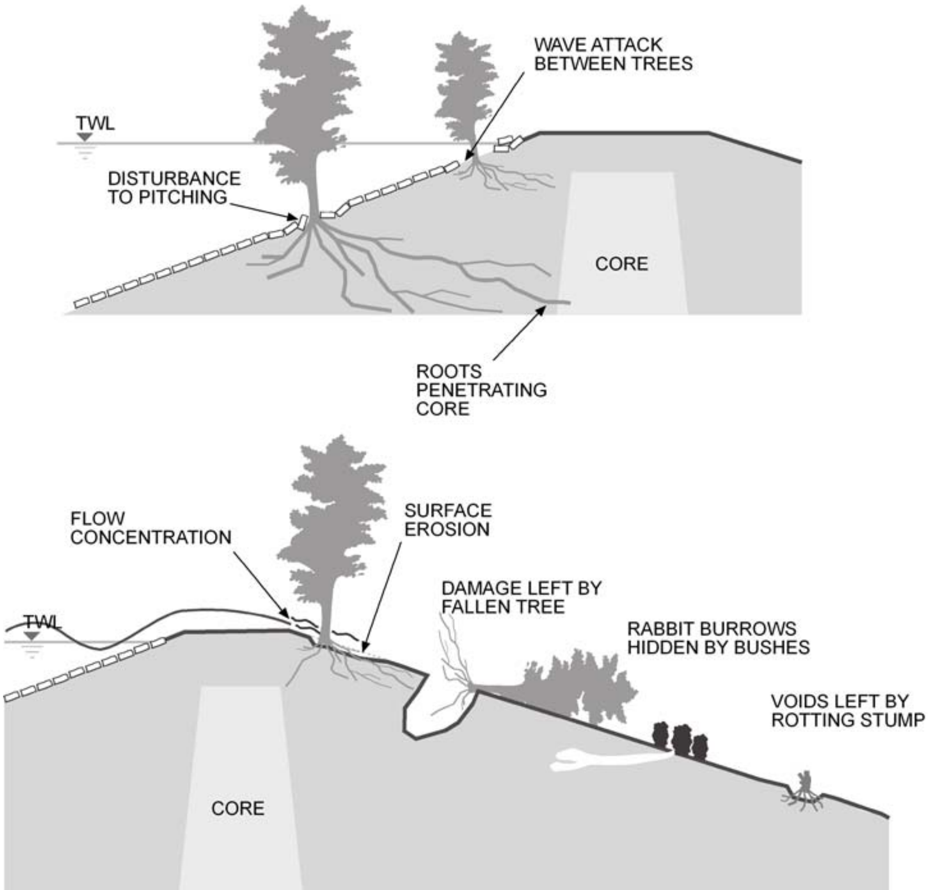

Figure 3.14 Damage caused by vegetation.

The hazard posed by vegetation or trees is discussed in BR 363, BR 303, CIRIA 161 and key papers by Hoskins (1993), Hoskins and Rice (1982), and Hughes and Hoskins (1994). Tedd and Hart (1985) studied four Pennine dams in relation to the influence of vegetation on remote monitoring using infrared thermography.

Erosion of grass protection of the upstream face and other surface erosion mechanisms were studied in the FLOODsite (Task 4) project and reliability equations are available.

This hazard closely relates to wave carry-over and wave slop (wave overtopping), with obstructions that result in flow concentration and additional loadings on the dam. As such, reference should be made to Sections 3.1.23 and 3.1.42.

The workshop highlighted this hazard as one of the most misunderstood hazards and, although guidance is available, the knowledge is significantly outdated. This is particularly relevant for small embankments and flood embankments, and guides such as CIRIA 161 require updating. Applicable legislation must be consulted, for example with regard to Tree Preservation Orders and habitats of protected species.

The hazard of vegetation is not mentioned explicitly in Defra's research strategy. However, this hazard relates to surface erosion and is closely linked with climate-change effects, which has received a high priority ranking of 6.

Available guidance on vegetation management must be updated. In the past few decades there has been a considerable amount of research on vegetation in general, some of which relates to performance of structures and earthworks. Guidance should include the findings of current and proposed international research, in particular the use of performance-based management techniques.

3.1.15 Features on the downstream face

Definition

Features such as sharp changes in geometry, public highways, paths, steps, seats, sculptures, ponds, walls, hedges, watermains or other services that exist on the downstream face obscure inspection and cause flow concentration if the crest is overtopped. Buildings are sometimes constructed on the downstream face.

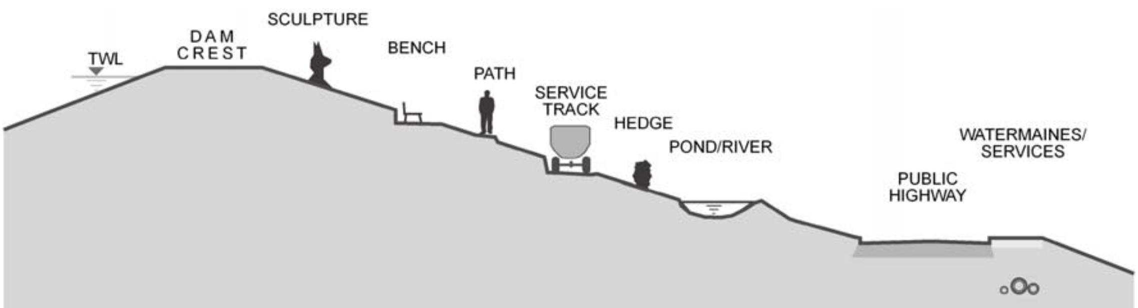

Figure 3.15 Damage caused by vegetation.

BR 363 and CIRIA 161 give guidance on features on the downstream face. Investigation of features on the downstream face and their implications about the state of the dam is covered in BR 303.

No papers that deal directly with features on the downstream face were found and this subject was not mentioned in the questionnaire.

This hazard closely relates to overflow and wave overtopping in the context of obstructions that cause flow concentration on the downstream slope. As such, reference should be made to Sections 3.1.23 and 3.1.42. The workshop emphasised a need to relate features on the downstream face to the processes that involve surface erosion in general and that require further guidance. Surface erosion on the downstream face is being addressed in international projects including FLOODsite (Task 4), the United States Army Corps of Engineers (USACE), the United States Bureau of Reclamation (USBR) and the United States Department of Agriculture (USDA). Note that the frequency of overtopping may increase as a result of climate change. Construction of buildings on the downstream face may result in stability issues, as well as concentrating erosion in the event of overtopping.

The Environment Agency's database of serious dam incidents lists those that involve surface erosion.

The Defra research strategy does not specifically mention the hazard of features on the downstream face. However, this hazard relates to surface erosion and is therefore also related to climate-change effects, which has received a high priority ranking of 6.

Further guidance is required on surface erosion, but international research is underway. Steps should be taken to raise the awareness of inspecting and supervising engineers and owners of the hazard of downstream features; this could be achieved by updating existing key documents and/or producing a practical checklist for inspections.

3.1.16 High pore-water pressures

Definition

Pore-water pressure higher than that allowed for in the design.
This can lead to increased seepage, hydraulic fracture or instability.

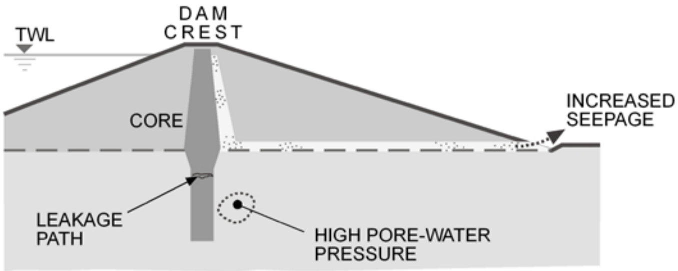

Figure 3.16 Damage caused by high pore-water pressure.

The hazard of high pore-water pressures is discussed in BR 303 and BR 363; ICOLD (1989a) refers to high pore-water pressures in dam foundations and CIRIA 148 refers to foundations of concrete dams. Additional information is given in academic papers including Bishop (1946,; 1957), Vaughan (1989), Dounias *et al*. (1996), Moffat (1975), Paton and Semple (1960) and Penman (1986, 1995). Measurement of pore-water pressures is discussed in Tedd *et al*. (1989), Bishop *et al*. (1964) and Wilkinson *et al.* (1969). Case studies that relate to pore-water pressures during construction include Selset (Bishop and Vaughan, 1962; Bishop *et al*., 1960, 1963), Brianne (Carlyle, 1973) and Audenshaw (Hughes and Lovenbury, 2000) dams. A case study of dam failure caused by high pore-water pressure involves Withens Clough dam, described in Arah (1975).

The Environment Agency's database of serious dam incidents gives a list of those that involve high pore pressures.

Both questionnaire and workshop indicated that no further research is required on this topic and that it is well understood. However, emphasis should be made on the correct interpretation of monitoring results, see Section 4.

The Defra research strategy does not specifically mention the hazard of high pore pressures.

No further research on high pore-water pressure is deemed necessary at this stage.

3.1.17 High uplift pressures on foundation

Definition
For concrete or embankment dams uplift pressures higher than allowed for in the design potentially lead to instability.

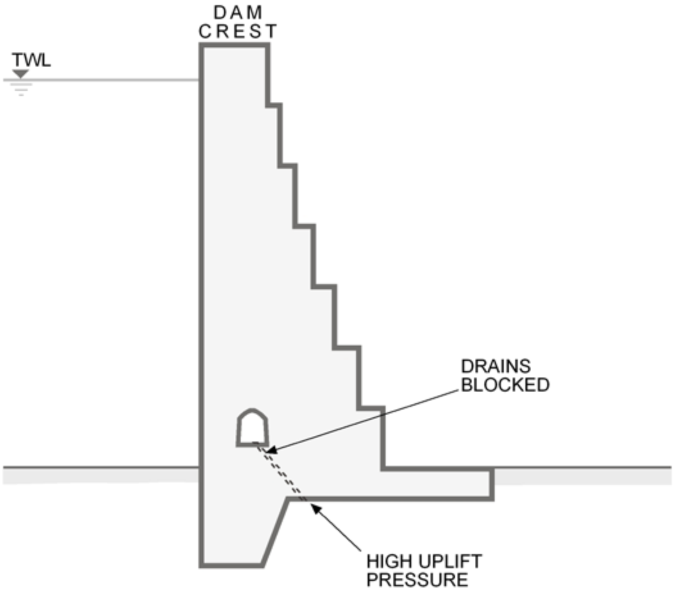

Figure 3.17 Instability caused by high uplift pressure.

Uplift pressures in concrete dam foundations are discussed in CIRIA 148. Historic case studies include Selset (Bishop *et al*. 1963), Laggan and Blackwater (Wallis *et al*., 2004), Upper Glendevon (Allen, 1975) and Loch Dubh (Moffat, 1969), and other academic papers that discuss concrete dams include those by Moffat (1975) and Ruggeri (2001). Van Nnortwijk *et al*. (1999) discuss the probability of dike failure caused by uplifting and piping.

Uplifting of impermeable foundation strata for flood defence structures was studied in the FLOODsite (Task 4) project and reliability equations are available.

The questionnaire highlights geotechnical hazards generally as lacking sufficient guidance.

Defra's research strategy identifies the need to explore non-linear numerical analysis of concrete dams and their foundations with a priority rank of 41.

Further guidance on high uplift pressures on embankment dams may be required. However, in the first instance guidance should be produced that takes into consideration findings of existing research on flood-defence structures.

3.1.18 High uplift pressures on lift joints

Definition
For concrete dams high uplift pressures on lift joints within the dam lead to instability and/or cracking at levels above the foundation. The same may occur within concrete elements of embankment dams.

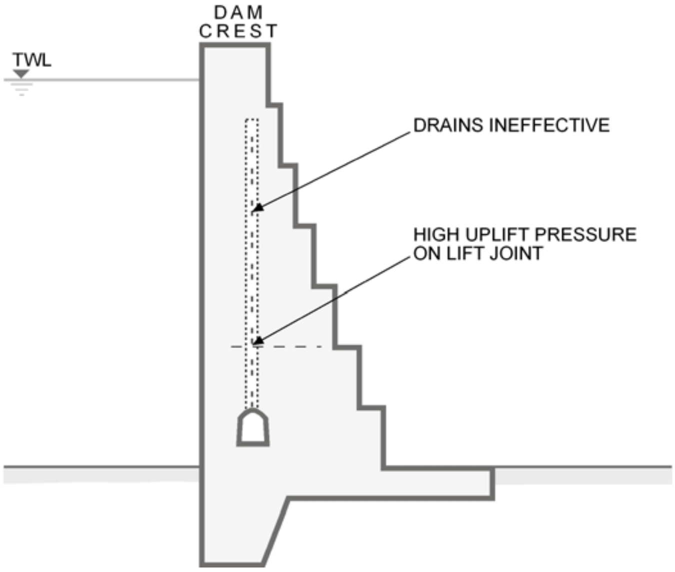

Figure 3.18 Effect of high uplift pressures on lift joints.

Comprehensive guidance on the lift joint is given in CIRIA 148 and ICOLD (1986b, 1997). Additional information can be found in other papers, such as Mackey and Morison (1988) and Brighton and Lampa (1991). Case studies include remedial works to old Italian dams (Terziani *et al*. 1988) and replacement of expansion joint seals at Clywedog dam (Mackey and Morison, 1988).

The responses to the questionnaire provide no indication that guidance currently available for this topic is insufficient.

Defra's research strategy identifies the need to explore non-linear numerical analysis of concrete dams and their foundations with a priority rank of 41.

No further research on uplift pressures on lift joints is deemed necessary at this stage. However, exploration of non-linear numerical analysis techniques has been recommended in Defra's strategy and will provide more information about this hazard.

3.1.19 Hydraulic fracture

Definition

Hydraulic fracture can occur where the pore pressure at a location in the core is higher than the minimum total earth pressure acting on a plane that crosses the core. Hydraulic fracture can lead to internal erosion.

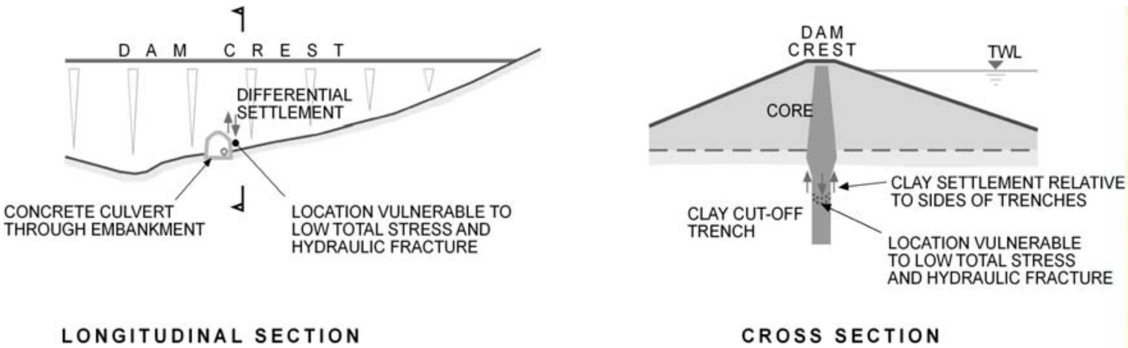

Figure 3.19 Hydraulic fracture can lead to internal erosion.

The subject is discussed adequately in BR 303 and BR 363, and in several key papers such as Atkinson *et al*. (1994), Charles and Watts (1987), Penman and Charles (1981), Tedd *et al*. (1987), Lofquist (1992) and Alonso (1997). Case studies that deal directly with problems confirmed as hydraulic fracture include Arminou and Hills Creek dams, which are discussed in Brown and Bruggemann (2002) and Jenkins and Bankofier (1972), respectively; and two cases of hydraulic fracture in Venezuelan embankment dams discussed in De Fries (1991). Comprehensive reviews of hydraulic fracture are given in Skempton (1987, 1989), which study several historical records and suggest indicators to assess embankment-dam susceptibly based on the dimensions of the core.

The Environment Agency's database of serious dam incidents lists those that involve hydraulic fracture.

Hydraulic fracture was not mentioned within the responses to the questionnaire. The workshop highlighted the link between hydraulic fracture and internal erosion and, as such, there is some need for further research and the process might not be as well understood as is commonly perceived.

The Defra research strategy does not specifically mention the hazard of hydraulic fracture.

Further research on the link between hydraulic fracture and internal erosion processes is required. This should be included in the ongoing research regarding internal erosion.

3.1.20 Blockage of spillway

Definition

The spillway is blocked by floating debris such as trees or ice, or by screens that can become blocked. Blockage is sometimes the result of vandalism. Blockage of the spillway can result in increased flood rise in the reservoir and overtopping of the dam.

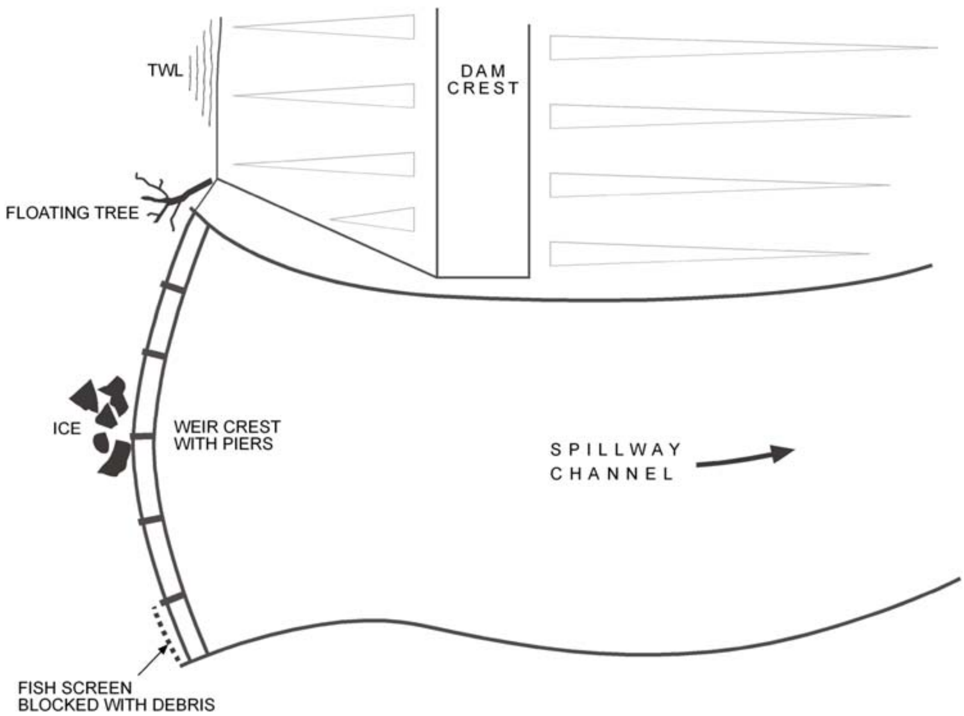

Figure 3.20 Spillway blockage.

Guidance regarding the blockage of spillways is given in BR 363, CIRIA 161, ICOLD (1987) and Environment Agency (2009b). Investigation of spillways is discussed in BR 303. Relevant papers include Bailey (1986), Baker and Gardiner (1994), Ballard and Lewin (2004), Godtland and Tesaker (1994), Griffith and Berry (1975), Hewlett and Baker (1992) and Lewin (2001). A known case study that involves a blocked spillway relates to the Maich dam and is described in Mann and Mackay (2009). The recent Environment Agency post incident report (2009) discusses a case study that involves overtopping of a non-statutory embankment dam because of a blocked culvert. Wearing *et al*. focused on tree blockage to spillways at the BDS 15th Biennial Conference (2008b).

Defra's research strategy includes research on masonry spillways with a rank of 3.

Research is underway in the form of a Science Report by the consultant Montgomery Watson Harza (MWH). It would be appropriate to broaden this research to spillways and overflow works in general or to include for additional research in this area. However, no specific research on blockage of spillways is required. This hazard could be highlighted in a practical checklist for inspections.

3.1.21 Inadequate energy dissipation

Definition

The energy dissipation arrangement at the end of a spillway has insufficient capacity to reduce the energy in the water to a safe level before it passes into the receiving watercourse. This can result in scour to the toe of the embankment or the river downstream.
This can be occur because of an undersized or non-existent stilling basin, or because the tailwater conditions are different from those assumed in the design.
Inadequate energy dissipation is not restricted to the toe of the spillway, and scour or erosional features can also develop further up the structure.

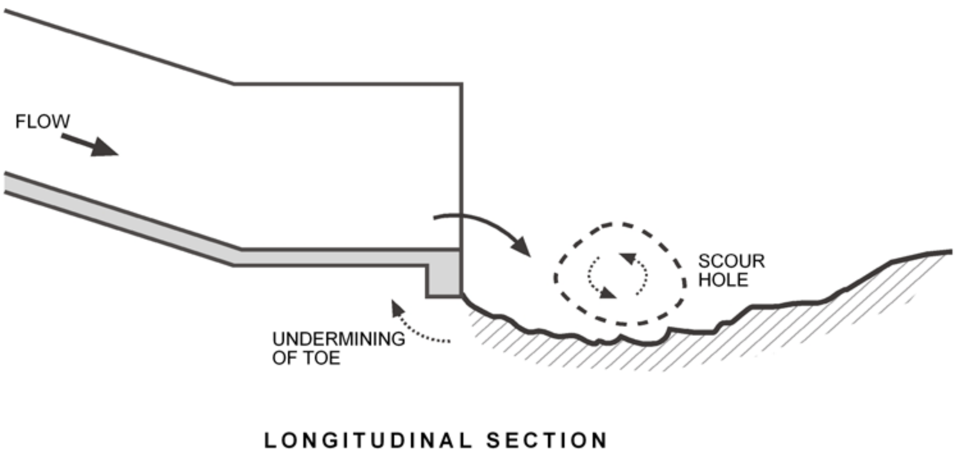

Figure 3.21 Effect of inadequate energy dissipation.

Energy dissipation is closely related to that of hydrodynamic forces described in Section 3.1.36. As such, similar guidance documents are also relevant here. The topic of hydrodynamic forces is discussed at length in ICOLD 058 (1987).

The workshop highlighted the need for further research on issues that relate to rate of failure and resilience, with a focus on remedial measures (for example, remediating scour holes). It was questioned whether the issue of inadequate energy dissipation is referred to in the ongoing research on masonry spillways.

Defra's research strategy highlights that masonry spillways requires further guidance with a priority rank of 3.

Research is underway in the form of a Science Report by the consultant MWH. However, it is not yet clear whether inadequate energy dissipation will be referred to adequately and this is concluded to require further guidance. It would be appropriate to broaden the research to spillways and overflow works in general or to include for additional research in this area.

3.1.22 Out-of-channel flow in spillway

Definition

Water is not contained in the spillway channel when it overflows from the reservoir. This can cause erosion of the embankment if the spillway channel is located close to it.
Out-of-channel flow may be caused by the size of the channel, its gradient, steps or pools, obstructions, superelevation, cross waves or bulking through air entrainment.

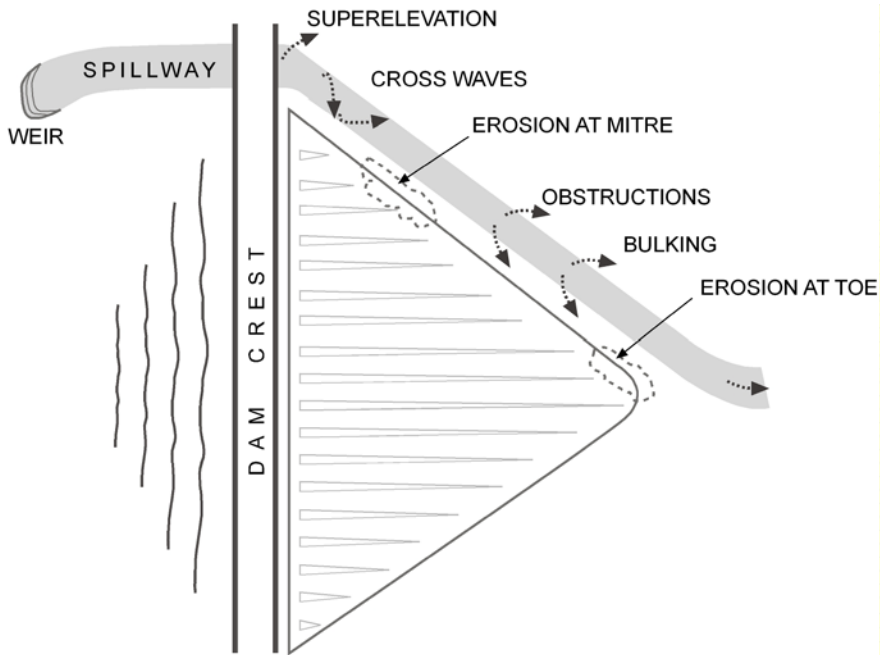

Figure 3.22 Out-of-channel flow in spillway.

Out-of-channel flow is closely related to spillway capacity described in Section 3.1.23. As such, similar guidance documents and case studies are also relevant here, in particular ICOLD 058 (1987), CIRIA 161 and CIRIA 148.

Key papers in which there is a particular reference to out-of-channel flow include Claydon *et al*. (2004), Bass (1982), Chanson (2000), Davison and Shave (2004), Ellis (1989), Hallas (1980), Heaton-Armstrong (1984), Law (1992), Myers (1967), Pinheiro *et al*. (2003), Bramley and Hewlett (1988), and several case studies investigated in the

Environment Agency *Post-incident report*s (2008, 2009). The case of Ulley reservoir is discussed in Mason and Hinks (2008).

The Environment Agency’s database of serious dam incidents lists those that involve out-of-channel flow.

The subject of erosion, as a result of overflow, was studied in the FLOODsite (Task 4) project and reliability equations are available. Research conducted within the FLOODsite project provides sufficient information regarding surface erosion as a result of out-of-channel flow.

The workshop highlighted the need for more guidance on the effects of out-of-channel flow on the area that surrounds the spillways and how susceptible the ground is to overflow.

Defra’s research strategy highlights that the subject of spillways requires further guidance with a rank of 3.

Research is underway in the form of a Science Report by the consultant MWH. It would be appropriate to broaden the research to spillways and overflow works in general or to include for additional research in this area.

Further research on the susceptibility of material to erosion and the rate of erosion may be required in the future, but this is not considered to be a high priority.

3.1.23 Overflow capacity exceeded

Definition

The overflow or spillway at the dam has insufficient hydraulic capacity to pass the design flood and maintain adequate freeboard.
This can result in overtopping of the crest and damage to the dam.

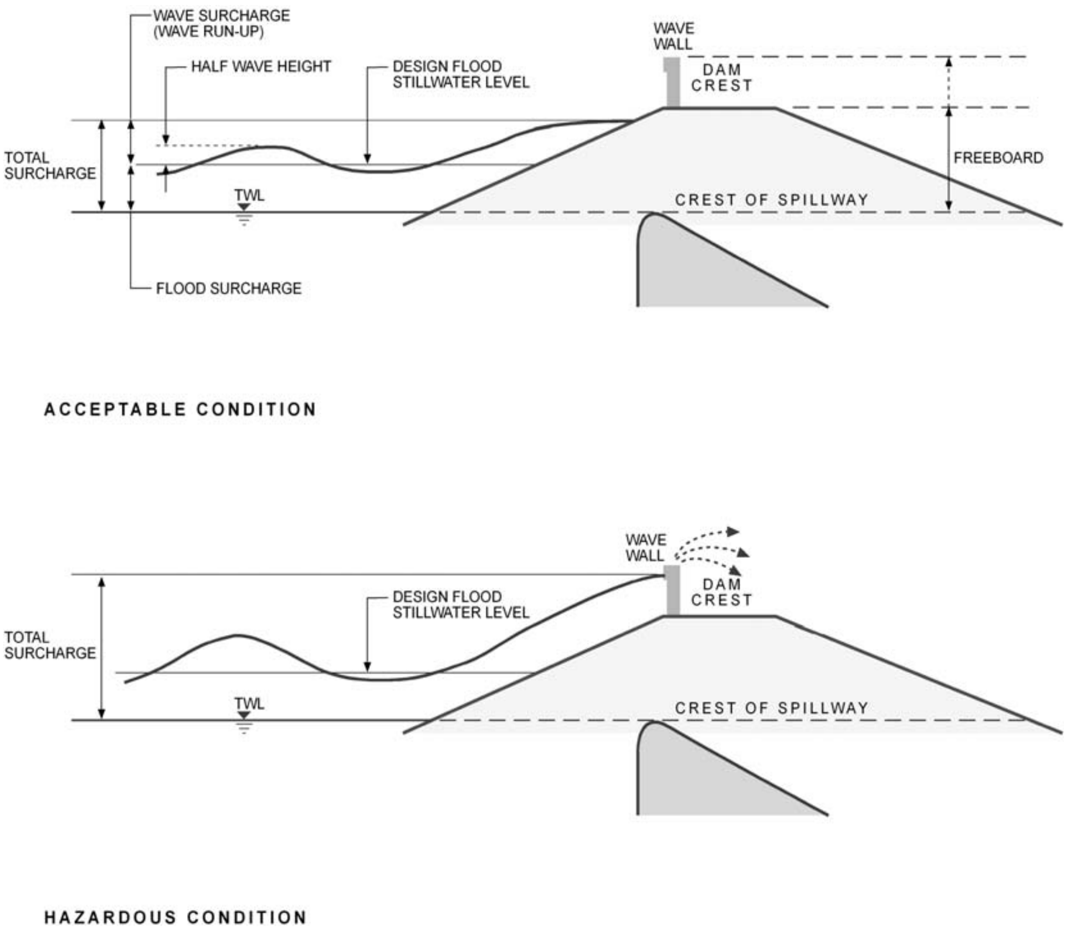

Figure 3.23 Acceptable and hazardous conditions for overflow capacity.

Research regarding spillway capacity or overflow adequacy is covered in numerous documents such as CIRIA 148, CIRIA 161, BR 363, Institution of Civil Engineers (1996), ICOLD (1987), ANCOLD (2000a) and Environmental Agency (2009b).

Additional information is included in Brown (2008), Ballard and Lewin (2004), Bass (1982), Charles (1986), Kennard and Bass (1988) and several papers by Lewin and co-workers (1986, 1988, 2000, 2001, 2002). Case studies include Roundhill, Banbury, Ulley, Rivelin, Redmires, Washburn Valley and Woodhead reservoirs by Ackers (1994, 2004), Mason and Hinks (2008), Claydon and co-workers (1996, 2004) and Chalmers (1990), respectively.

The Environment Agency’s database of serious dam incidents lists those that involve spillway capacity being exceeded.

FLOODsite (Tasks 2, 4 and 7) provides valuable information on erosion as a result of overflow and overtopping failures. Both FLOODsite and CIRIA 14 discuss spillway capacity, and reliability equations are available on erosion as a result of out-of-channel flow and overtopping failures.

The workshop highlighted the direct link between this hazard and small embankment and flood defences.

Defra’s research strategy highlights that the subject of masonry spillways requires further guidance with a rank of 3; research is underway in the form of a Science Report by the consultant MWH.

There is a need for further research on the hazard of spillway and overflow capacity being exceeded and guidance on improving resilience. In the first instance, research on flood banks should be used to inform the reservoir community.

3.1.24 Deterioration of core

Definition
Puddle clay, asphaltic or concrete cores in embankment dams can deteriorate because of differential settlement, uneven loading, chemical or other attack. This can lead to cracking and the development of seepage paths.

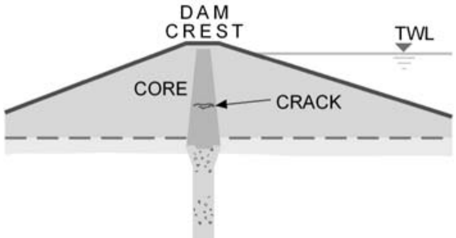

Figure 3.24 Core deterioration.

The hazard of puddle-core deterioration is discussed indirectly in documents such as CIRIA 148 and BR 303. Concrete and clay cores are discussed in the historic papers by Watts (1904) and Gourley (1922). Grouting of puddle clay cores is discussed in St John *et al*. (1998), Ray and Bulmer (1982). Information about the case study of Balderhead dam is given in Kennard (1964) and Kennard *et al*. (1967a). The behaviour of clay cores is studied in key papers by Vaughan *et al*. (1970) and Charles (1989). No research was found on asphaltic cores.

The Environment Agency's database of serious dam incidents lists those that involve deterioration of the core.

Although information is available on concrete deterioration and clay-core deterioration, very little of the information found related directly to concrete-core walls, sometimes installed during remedial works to ageing clay-core dams. This subject was not mentioned in the questionnaire.

The workshop revealed a need for further guidance on concrete cut-offs and different types of chemical attacks in general, which are discussed in Sections 3.1.25 and 3.1.26.

Defra's research strategy highlights that the wider subject of deterioration of concrete requires further guidance with a rank of 25.

Further research is required on the deterioration of cores and some of this could be incorporated into wider research on the deterioration of concrete. This hazard should be included in any future updates of key documents.

3.1.25 Concrete cut-off deterioration

Definition

Concrete cut-offs in embankment dams can deteriorate because of differential settlement, uneven loading and chemical or other attack. This can lead to cracking and the development of seepage paths along the dam foundations.

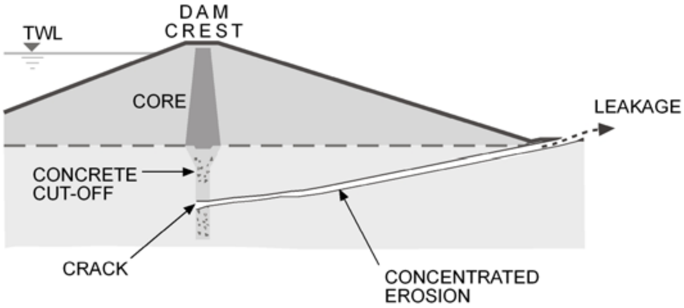

Figure 3.25 Core deterioration.

The construction of concrete cut-offs is discussed in CIRIA 161 and CIRIA 148. Case studies are discussed in Bowtell (1988, 1991), Dounias *et al.* (1996), Brown and Bruggemann (2002), Barr *et al*. (1998), Tedd and Jefferis (2000), Smith (2000), Broad (2000) and Campbell (1994). Bishop *et al.* (1963) discuss the efficiency of concrete cut-offs in great detail. Historic papers by Watts (1896, 1906) discuss cut-off trenches in general and with reference to the case studies of Langsett and Underbank dams.

The Environment Agency's database of serious dam incidents lists those that involve concrete cut-off deterioration.

The questionnaire did not highlight any issues that involve cut-off trenches, although reference to chemical attack on dam components was mentioned as requiring further research. The workshop identified that the deterioration of concrete cut-offs requires further research. That the majority of guidance deals with concrete cut-off trench construction rather than deterioration with time or through chemical attack supports this.

The Defra research strategy highlighted that concrete cut-offs and grout curtains required further research with a priority rank of 28.

It is concluded that guidance is required on concrete cut-off deterioration, and this should be incorporated in any future research that arises from Defra's strategy.

3.1.26 Concrete deterioration by chemical or other attack

Concrete may deteriorate and fail through:

- attack by sulphates in soils, sulphate-bearing waters, very soft pure water, acidic water and seawater;
- aggressive agents of industrial origin;
- alkali-silica reaction;
- by the action of frost in freezing and thawing;
- cracking caused by thermal movements and shrinkage, and moisture movement;
- corrosion of reinforcement;
- attack by wave action on lift joints on the upstream face of a dam.

(Source: CIRIA 148)

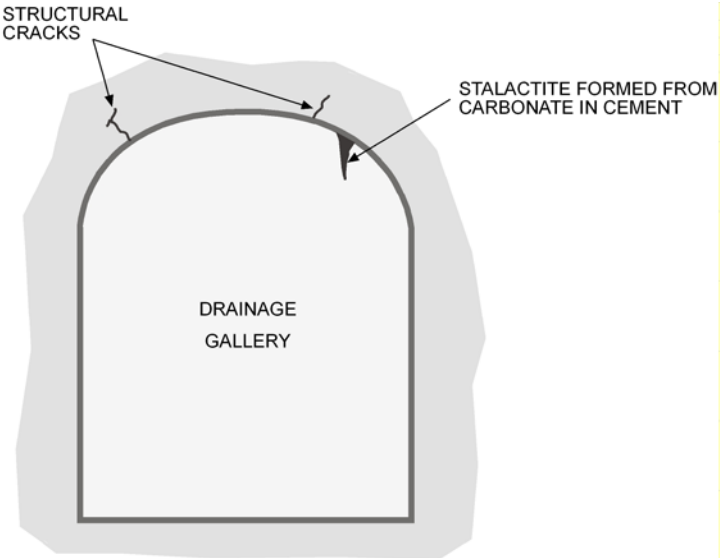

Figure 3.26 Concrete deterioration.

Concrete deterioration is discussed extensively in CIRIA 148 and Eurocode 2. Additional information is included in Charles and Tedd (2000), Dempster and Findlay (2004), Curtis and Milne (1984) and Brighton and Lampa (1991). Case studies that involve Maentwrog, Blackwater and Lednock dams are discussed in Davie and Tripp (1991), Martin (1982) and Pasteur (2000), respectively.

Guidance on chemical attack on concrete dams is discussed in CIRIA 148 and several academic papers were identified. Hammersley (1988) and ICOLD (1991) deal with the subjects of alkali–silica reactions (ASRs) and alkali–aggregate reactions (ARRs), Cassidy (1988) discusses chemical attacks in general with some application regarding dams, and Davies and Reid (1997) and Pye and Miller (1990) discuss geochemical aspects of dam construction and deterioration. Case studies that involve Altnaheglish, Val-de-la-Mare and Roadford dams are referred to in Fitzgerald (1975), Coombes *et al*. (1975) and Davies and Reid (1997), respectively.

The Defra research strategy does not mention of deterioration by chemical or other attack. However, the strategy identifies that the degradation of concrete dams requires further research with a priority rank of 25.

Updating of existing guidance on deterioration and degradation of concrete is required and is included in projects that arise from Defra's strategy that involve degradation and repair of concrete dams. Reference should also be made to Eurocode 2.

3.1.27 Deterioration in foundation soil strength

Definition

Deterioration of the foundation through:

- through loss of strength under permanent or repeated actions;
- through erosion and solution.

(ICOLD definition, 1994)

Examples:

- Reduction in strength of shale foundation under a rockfill dam that leads to permanent deformation of the upstream membrane.
- Solution of gypsum in dam foundation that leads to solution passages.

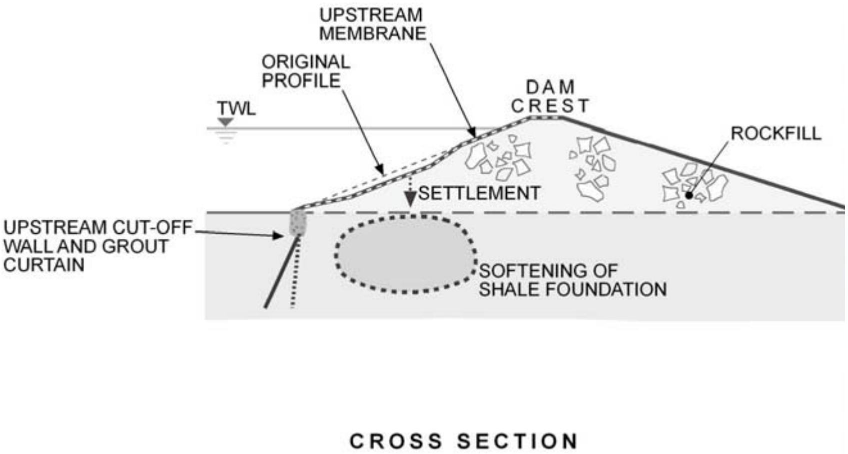

Figure 3.27 Deterioration in foundation soil strength.

Deterioration of foundation soil strength is discussed in ICOLD (1994) and ICOLD (1993a). ICOLD (1988) refers to embankment dams built on glacial deposits. Key academic papers include Charles (1993), Bedmar and Araguas (2002) and Cardoso and Fernandes (2001). Case studies include O'Mahony and Haugh (2002), which discusses remedial works at Leixlip dam, and Caballero *et al.* (1995), which reviews the erosion of gypsum foundations at Caspe dam. Vaughan *et al*. (1991) review foundation problems at Carsington dam.

The Environment Agency's database of serious dam incidents lists those that involving the deterioration of foundation strength.

The questionnaire highlighted this subject as one that required further guidance. The workshop highlighted the need to link the deterioration of foundation soil strength with internal erosion and seepage through the dam's foundations. Reference should be made to Sections 3.1.6–3.1.11.

Defra research strategy does not mention the deterioration of foundation soil strength. There is a relationship with internal erosion and seepage through dam foundations, and internal erosion has been ranked number 1 in the strategy.

Further guidance is required on the deterioration of foundation soil strength.

3.1.28 Deterioration of concrete or rock foundation

Definition
Deterioration of concrete or rock at the foundation of a concrete dam to an extent that affects stability.

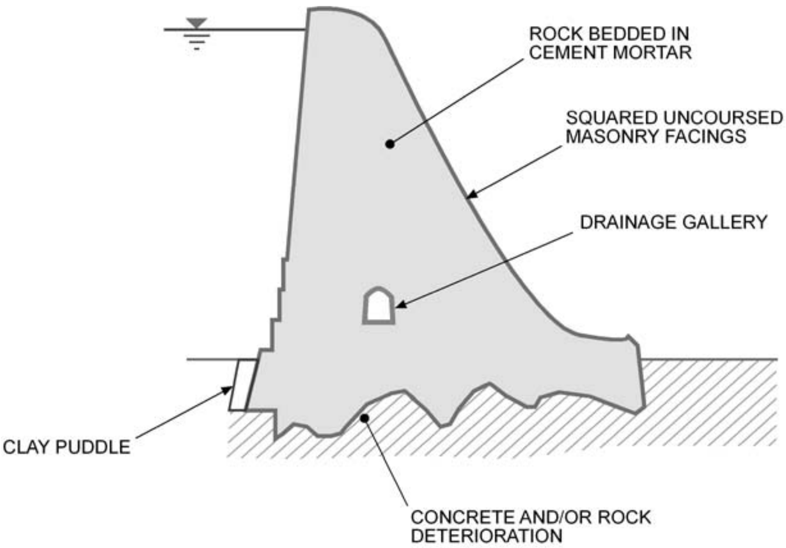

Figure 3.28 Deterioration of concrete rock foundation (based on Figure 1.1 from CIRIA 148).

Concrete foundations and abutments are discussed in CIRIA 148, and ICOLD (1993a) provides a comprehensive guide for rock foundations. Deterioration of concrete dams is discussed in Davie and Tripp (1991), Dempster (2004), Crosthwaite and Hunter (1967) and Brighton and Lampa (1991), some of which refer to deterioration of concrete foundations. O'Mahony and Haugh review a case study that involved Leixlip Dam in which concerns were raised as to the stability of the dam because of the presence of weak layers of gouge material interspersed with limestone layers in its rock foundation. Eurocode 2 is a general key reference for concrete structures.

The Environment Agency's database of serious dam incidents lists those that involve the deterioration of concrete or rock foundation.

No direct reference to lack of guidance on this hazard was highlighted in the questionnaire. The workshop highlighted the issue of concrete–rock interface and the relationship between climate-change effects, such as significant cyclic changes in water levels that lead to deterioration, rather that consolidation. However, it was commented that this topic is not relevant in the UK, where there is a majority of embankment dams. It was concluded that it would be of benefit to re-issue the current guidance.

Defra research strategy identifies the need to explore non-linear numerical analysis of concrete dams and their foundations with a priority rank of 41. It also identifies that degradation of concrete dams requires further research with a priority rank of 25.

Updating of existing guidance on deterioration and degradation of concrete dams and their foundations is required and should be incorporated in projects that arise from Defra's strategy involving degradation and repair of concrete dams, if possible.

Reference should also be made to Eurocode 2. This hazard is not considered to be a high priority.

3.1.29 Deterioration of upstream membrane

Definition

Upstream membranes may deteriorate through wave, chemical, environmental or other attacks, such as human activity. Damage to upstream membranes can cause serious leakage, which in turn could lead to internal erosion.
(Source: BR 363)

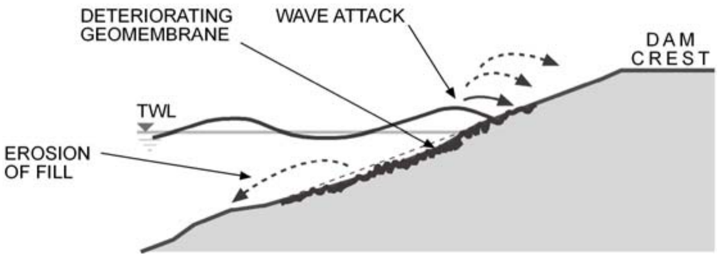

Figure 3.29 Deterioration of upstream membrane.

Existing guidance on the subject of upstream membranes is given in BR 363, BR 303, ICOLD (1981) and CIRIA 161 – the latter focuses on construction rather than long-term deterioration. Additional information is provided by Tedd (1999), Girad (2004), Carter *et al.* (2004), Scuero and Vaschetti (1998, 2004), Sembenelli and Cuniberti (1988), Case studies include Bakethin (Rocke, 1980) dam and Washburn reservoirs (Farmery, 2003).

The Environment Agency's database of serious dam incidents lists those that involve the deterioration of upstream membranes.

The workshop highlighted the need to update guidance on small reservoirs and flood-type reservoirs. It was noted that in the UK most practical examples of dams with an upstream membrane are farm reservoirs.

Defra strategy identifies two key areas that are linked to the deterioration of upstream membranes. These include wave protection and the direct and indirect impacts of climate change (projects ranked 38, 6 and 47, respectively).

The existing guidance on upstream membranes needs to be updated and should focus on implementing research carried out within the flood-type reservoirs, such as those in FLOODsite Task 4.

3.1.30 Deterioration of concrete facing or asphaltic concrete

Definition

For modern rockfill dams, concrete or asphaltic concrete facing may deteriorate through wave, chemical, environmental or other attacks, such as human activity. Joints can be the points of weakness that allow the initiation of damage. Damage to concrete protection can cause serious leakage, which in turn could lead to internal erosion.
Source: BR 363 and BR 303

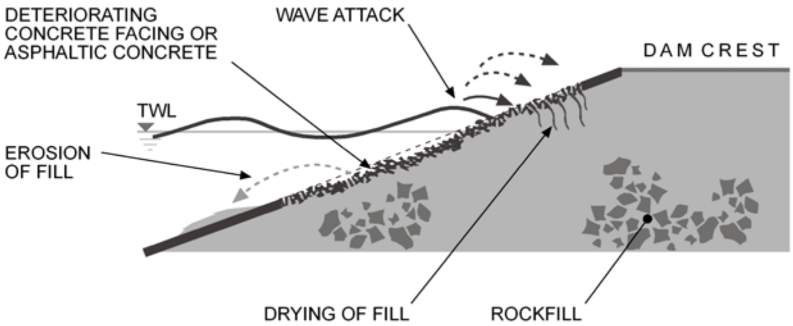

Figure 3.30 Deterioration of concrete facing or asphaltic concrete.

Similar guidance to that in Section 3.1.29 is relevant to concrete and asphaltic concrete facing. Additional references include Hopkins *et al*. (2002), Tedd *et al*. (1991), Wilson and Robertshaw (1998) and Penman and Hussain (1984). Johnston and Evans (1985) and Duncanson and Johnston (1988) discuss the case study of Colliford and Roadford reservoirs. The Winscar dam case study is discussed in length in BR 303, Carter *et l.* (2002a, 2002b) and Claydon *et al*. (2003).

The Environment Agency's database of serious dam incidents lists those that involve deterioration of concrete or asphaltic concrete.

The FLOODsite project (Task 4) reviews mechanisms of physical erosion of the upstream face, such as grass, clay, rock armour and gabion protection. A review of subsoil erosion through block mats, concrete mattresses, gabions and geosystems is also taken together with mechanisms of uplift and erosion of asphaltic or other types of revetments. All these mechanisms are given reliability or limit-state equations to be used in analysis.

The Defra strategy identifies two key areas linked to deterioration of asphaltic concrete blankets. These include wave protection and the direct and indirect impacts of climate change (projects ranked 38, 6 and 47, respectively).

The existing guidance on upstream membranes needs to be updated and should focus on implementing research carried out within the flood-type reservoirs, such as those in FLOODsite Task 2. Reference should be made to Eurocode 2.

3.1.31 Chemical attack on fill or rockfill

Definition
Fill or rockfill may deteriorate and breakdown as a result of: • attack by sulphates in soils, sulphate-bearing waters, very soft pure water, acidic water and seawater; • aggressive agents of industrial origin; • by the action of frost in freezing and thawing; • cracking because of thermal movements, as well as shrinkage and moisture movement.

There does not seem to be any guidance about geochemical attack on rockfill dams and relatively few research papers were identified for either embankment or concrete dams. ICOLD (1982, 1989b, 1993b, 1993d) gives guidance on rockfill dams (but it does not include information on chemical deterioration) as does USBR (Dewey and Gillette 1993). Johansen *et al*. (1997) and Norstedt and Nilsson (1997) discuss internal erosion of rockfill in some Scandinavian dams. However, there seems to be insufficient guidance about chemical attack on rockfill dams generally and this was also highlighted in the workshop.

For more detail regarding this hazard, see Section 3.1.31.

Defra research strategy does not mention the subject of deterioration of fill or rockfill by chemical attack. However, climate change was identified as requiring further research with a priority rank of 44 and there is an indirect link between climate change and chemical attack (for example, because of a change in water geochemistry or pollution).

It is concluded that the subject of chemical attack on rockfill dams should be considered for incorporation in projects that arise from Defra's strategy on climate change (projects ranked 6 and 47).

3.1.32 Blocked drains and relief wells

Definition
Blockage of drains or relief wells so they no longer carry out their design function to control uplift pressure. This can affect the stability of concrete and embankment dams.

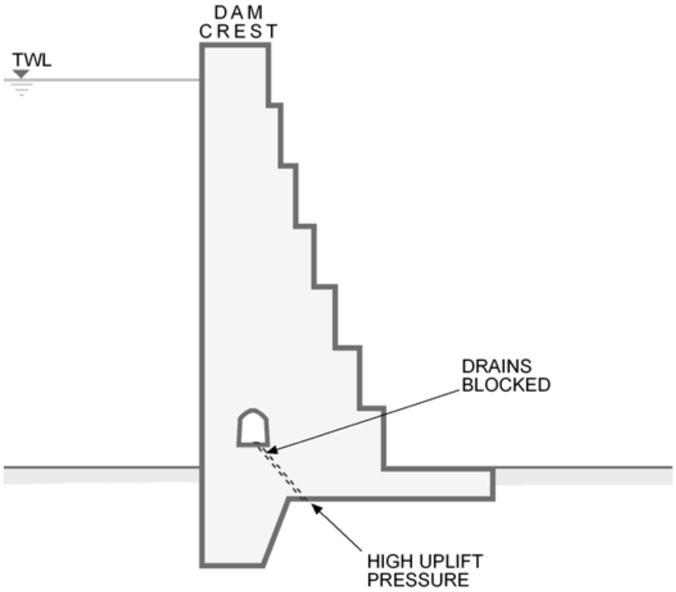

Figure 3.31 Effect of blocked drains.

CIRIA 161, CIRIA 148 and ICOLD (1994) provide Information on the design of drains and relief wells. Additional guidance is given in key references such as BR 363 and BR 303. Academic papers include Braun (1990), Mlynarek (2000) and Sheppard and Little (1955), Lafleur *et al*. (1993), Kennard (1988), Schulze and Brauns (1988), Penman (1986). Case studies can be found in Malia (1992) and Sills (1975).

Answers to the questionnaire and the workshop emphasised the role of the inspecting engineer.

Defra research strategy does not mention the subject of blocked drains or relief wells.

No further research on blocked drains and relief wells is deemed necessary at this stage. However, the hazard could be included in a practical checklist for inspections.

3.1.33 Blocked screens

Definition

Screens on the upstream end of draw-off or scour pipes become blocked, which reduces flow capacity.

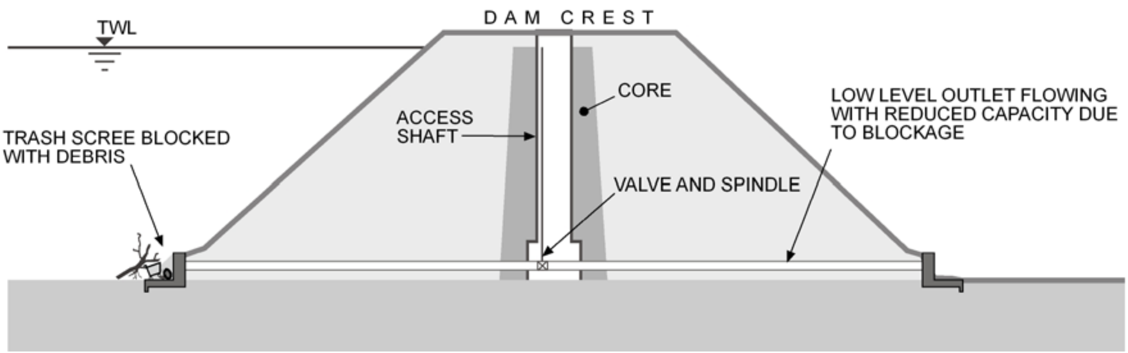

Figure 3.32 Effect of blocked screens.

General guidance on this hazard is given in CIRIA 161, CIRIA 170, BR 363, BR 303 and Lewin and Whiting (1986). Case studies that involve draw-off works can be found in Arah (1975) and Gallacher (1988), which discuss Gladhouse, Loch Cote and Withens Clough dams.

The workshop highlighted some documents and research initiatives:

- the recently published Environment Agency *Trash and Security Screen Guide* (2009d);
- research currently underway on sedimentation in bottom outlets and downstream screens, some of which is funded by Swisselectric Research;
- guidance in CIRIA 161 and CIRIA B14, in which the latter focuses on maintenance issues on the blockage of silt and oil traps, and sedimentation basins.

Defra's reservoir safety research strategy specifies a proposed project on the location, design and maintenance of fish screens, which has been given the lowest priority ranking of 49.

No further research on blocked screens is deemed necessary at this stage. However, the hazard could be included in a practical checklist for inspections.

3.1.34 Other damage to ancillary structures

Definition

Damage to or deterioration of ancillary structures, accidental or deliberate, that results in them not being able to carry out their intended function.
Examples:

- draw-off towers can be displaced by unbalanced forces from embankment movement, which cause cracking that can be transmitted to pipework;
- tunnels and pipes can be cracked by foundation settlement;
- spillway gates can be damaged by floating logs;
- corrosion of bolts, valves and bearings;
- graphitisation of cast-iron pipes;
- closure of spillway gates not possible because of a reduced gap between piers (caused by concrete expansion that arises from ASR);
- cracking of tunnels caused by differential settlement and potential collapse.

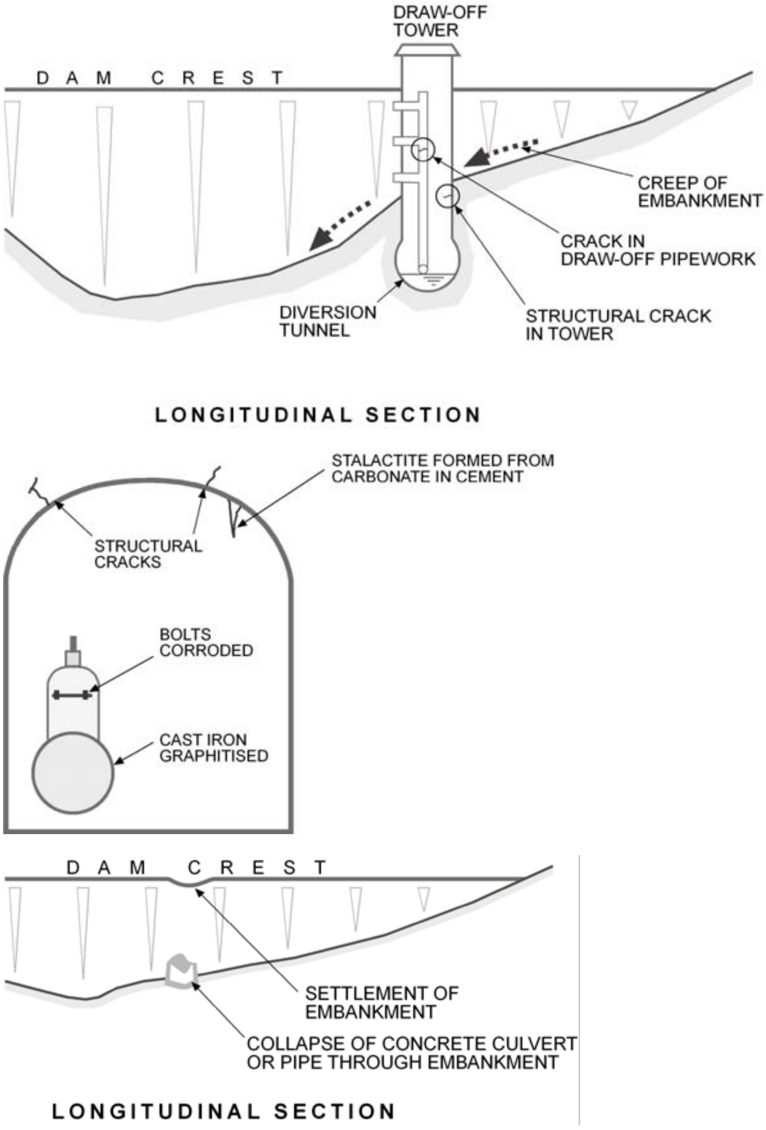

Figure 3.33 Damage to the ancillary structure.

Deterioration of ancillary structures is discussed in CIRIA 148, CIRIA 161, BR 363, BR 303 and ICOLD (1983a). Eurocode 3 provides key guidance as to the design and construction of steel structures. Deterioration of spillways was investigated by Baker and Gardiner (1994) and Charles (1986). A case study by Dempster and Lannen (2002) relates to refurbishment works at Breaclaich Dam and Davie and Tripp (1991) discuss deterioration of Maentwrog dam. Charles and Tedd (2000) and Curtis and Milne (1984) discuss concrete deterioration in general and some reference is given to ancillary works as well. A paper by Goodie (2001) involves deterioration of pipeworks and valves and a key paper by Moffat (1982) reviews deterioration of dams as a whole.

The hazard discussed here was not highlighted in the questionnaire. However, the workshop showed that this hazard is related principally to other hazards in this report, such as in Sections 3.1.10, 3.1.32, 3.1.33, 3.1.35 and 3.1.38. As such, conclusions about it depend on the type of ancillary structure discussed. Moreover, comments from the workshop suggested that not all types of damage or deterioration to ancillary structures can be covered by one single comprehensive document and as such the role of the inspection engineer is critical.

The Defra research strategy recommends a review of several types of ancillary structures:

- **auxiliary spillways;**
- **tunnel repairs;**
- **pipes and valves;**
- **mechanical and electrical equipment;**
- **draw-off works;**
- **procedures for the assessment of intake towers and gates;**
- **fish screens.**

These studies should consider the vulnerability of structures to deterioration or damage. The current study concludes that at this stage no further guidance or research is required beyond that of the projects identified in Defra's strategy.

3.1.35 Failure of controls, valves or gates

Definition

The control system or valves fail to operate as required. This can result in no flow or uncontrolled flow.
Failure of a control gate to open or close as required to control water level.
Examples:

- Failure of a spillway crest gate to open during storm conditions that results in flood-water levels higher than designed.
- Failure of an off-stream storage reservoir control gate to close during inflow conditions that results in stored water levels higher than designed.
- Obstruction to gate operation that results in failure of the control gate.

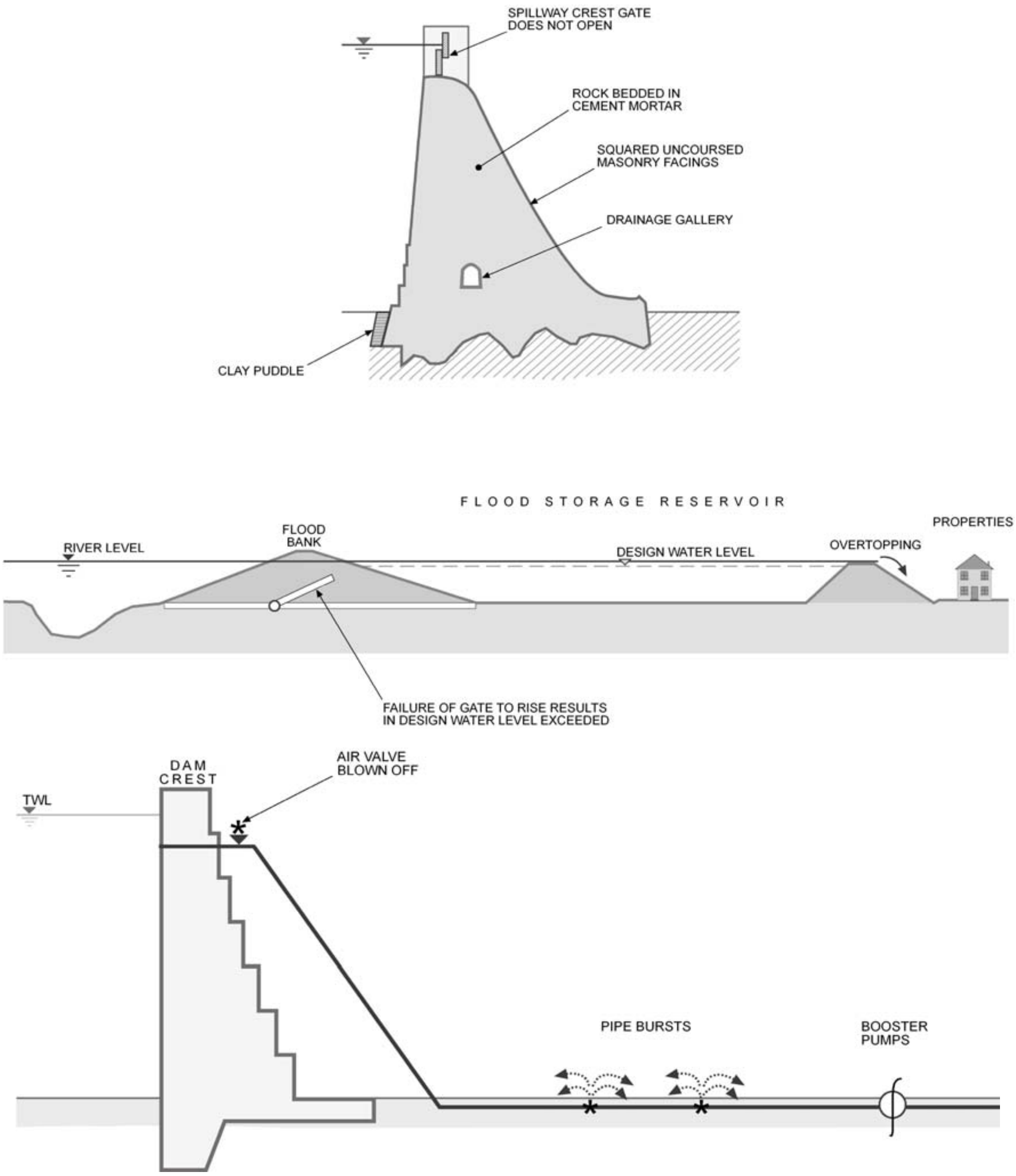

Figure 3.34 Effect of failure of controls, valves or gates.

CIRIA 170 gives comprehensive guidance on the design, operation, maintenance, monitoring and risks related to valves and pipework. Additional guidance is given in key references such as CIRIA 161, BR 363 and BR 303. Papers include Enston and Latham (2002), Pohl (2000), Case studies that involve failure of controls or valves are given in Lewin and Whiting (1986), and Gray (1988), which discuss reservoirs in the Strathclyde region, and Shepard (2001, 2002), which reviews failures at Ladybower reservoir.

The questionnaire raised the hazard of failure of pipes and valves as requiring further guidance in.

Gate failure is discussed in CIRIA 148, CIRIA 161 and ICOLD (1987). A significant number of papers were identified that discuss many aspects of spillway, tidal, flood and fuse gates, such as Ackers and Hughes (1988), Cassidy (2000), Ballard and Lewin (2004), Lewin and Hinks (2001), Lewin and Whiting (1986), Lewin (1988, 2000, 2008), Sandilands and Noble (1998), Townshend and Lund (2002) and Chevalier *et al*. (1996). Seismic evaluation of flood gates was studied by Daniell and Taylor (2000). Risk assessment for flood gates is investigated in Sandylands and Noble (1998). Hinks *et al*. (2003b) review extreme events in reservoir safety and also include gate-failure hazard estimation. In addition, the subject is briefly referred to in BR 363. Lewin (2008) reviews vibration caused by spillway gates.

Case studies include the Torr Achilty reservoir (Sandilands and Seaton, 1996), Dove Stone reservoir (Gardiner, 1996) and Brent Reservoir (Hughes and Kelly, 2002). Three additional case studies were investigated by Noble and Lewin (2000).

The workshop highlighted the need to incorporate information from other engineering fields and the importance of this hazard to small reservoirs.

Defra's research strategy recommends that existing guidance on controls, valves and gates need to be reviewed and updated (ranked 22, 26 and 45).

The current study supports Defra's recommendation above regarding existing guidance on controls valves and gates. Reference should be made to Eurocode 3. Although there is existing and planned research, there would be benefit in gathering data on old reservoirs, in particular those under 25,000 m^3, which are to be regulated in future (see Section 1.1.1).

3.1.36 Hydrodynamic forces that result in structural damage or failure

Definition

Forces exerted by flowing water in spillways apply impact forces to walls and energy dissipaters.
These can cause penetration of masonry by high-pressure water, which results in structural damage or failure.

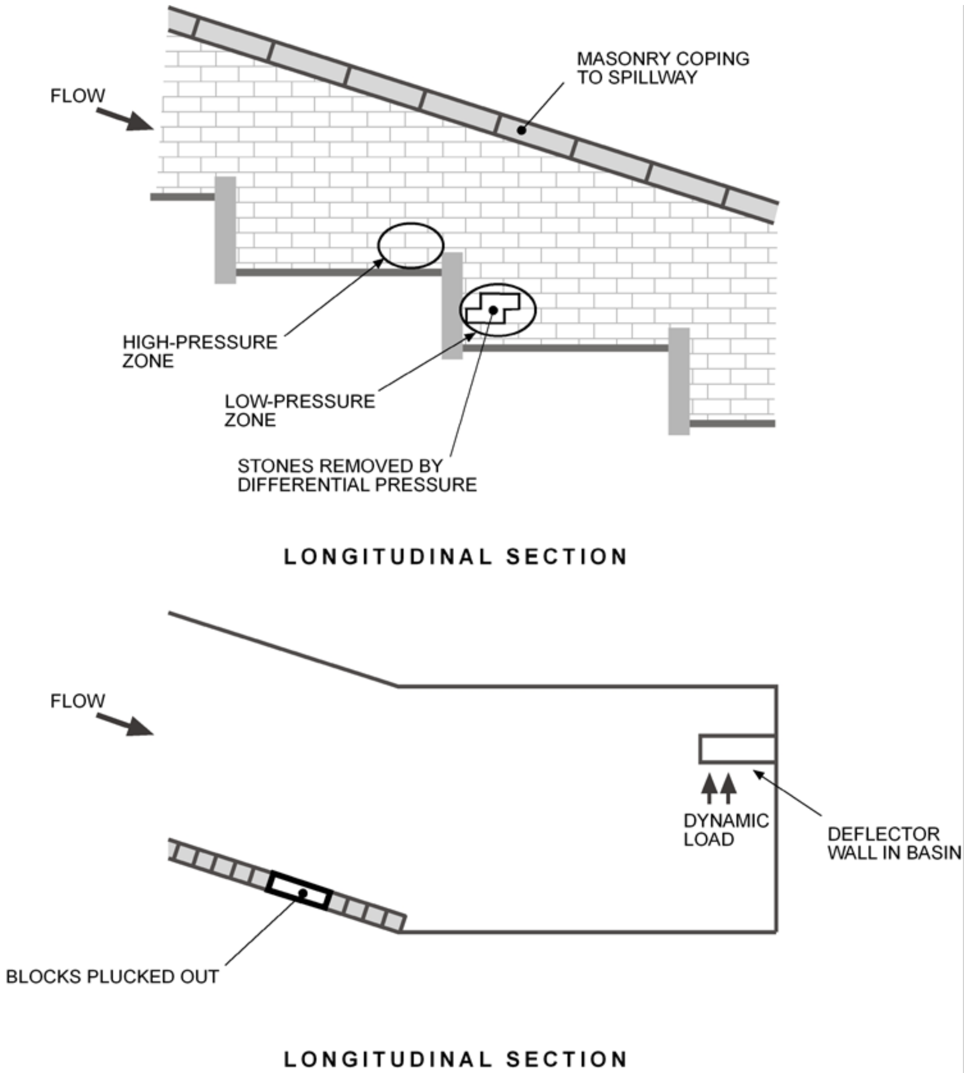

Figure 3.35 Hydrodynamic forces that result in structural damage or failure.

The subject of hydrodynamic forces is closely related to that of spillway capacity described in Section 3.1.23. As such, similar guidance documents and case studies are also relevant here, in particular ICOLD (1987). Academic papers and case studies identified that refer to spillway hydraulics include Ellis (1995, 1988, 1989), Etheridge (1996), Woolf and Hacker (2002) and Mason *et al*. (2006).

The workshop concluded that further research on hydrodynamic forces is required.

Defra's research strategy highlights the subject of masonry spillways as one that requires further guidance with a priority rank of 3; *Research* is underway in the form of a Science Report by the consultant MWH*.*

This study concludes that it would be appropriate to broaden the research to spillways and overflow works in general or to include for additional research in this area.

3.1.37 Local run-off on mitre that results in erosion

Definition

Run-off from natural ground concentrated at the mitre of the dam, on the upstream or downstream side. This can cause local erosion.

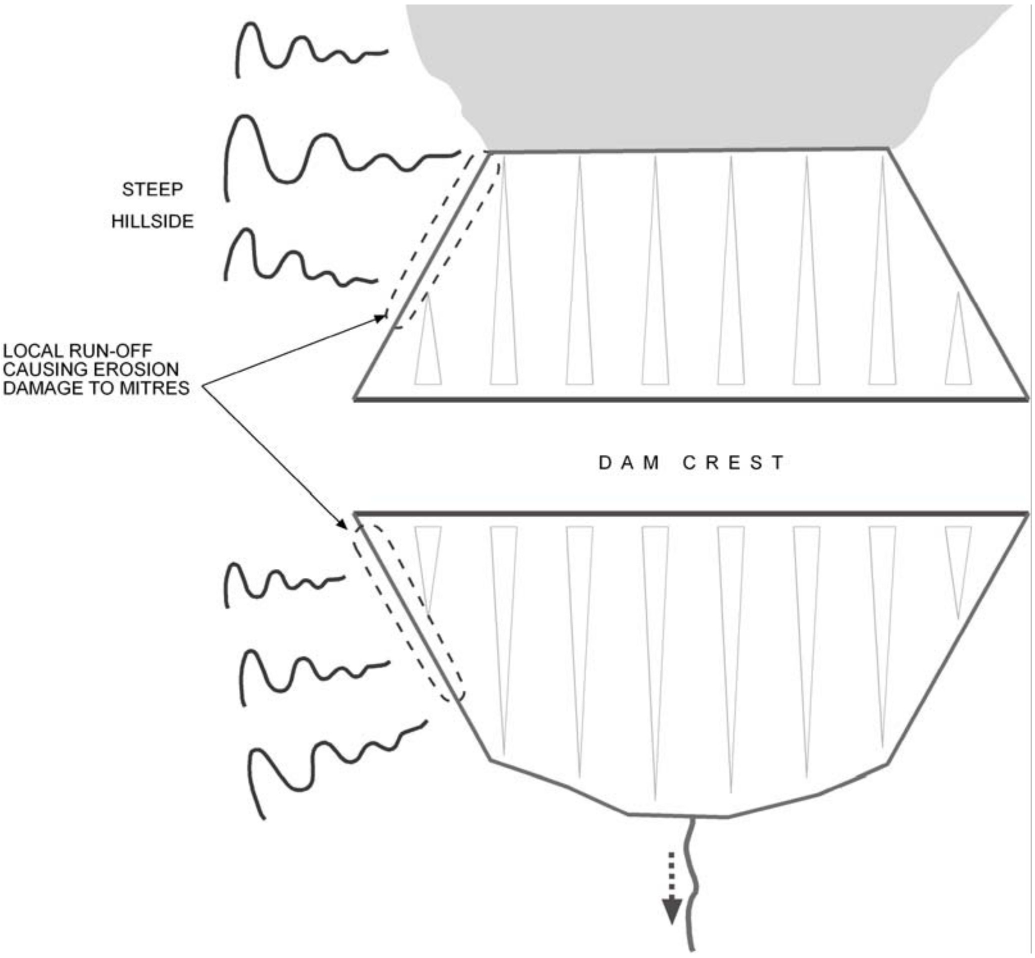

Figure 3.36 Local run-off on mitre that results in erosion.

BR 363, BR 303 and CIRIA 161 give guidance on run-off along the downstream slope or mitre of embankment dams. Academic papers identified were related mostly to case studies such as Altnehglish, Bilberry, Haweswater, Cowlyd and Maich dams, described in Fitzgerald (1975), Harrison (1997), Hopkins and Wickham (1988), Knight (1975) and Mann and Mackay (2009), respectively.

Surface erosion is closely related to local run-off on the mitre of the dam and is addressed in international projects, including FLOODsite (Task 4), USACE, USBR and USDA.

The workshop identified a need for a guide that focuses on design requirements for mitres. However, contradictory comments focused on the judgement of the designer, which suggests that no guidance is necessary.

Defra's research strategy does not specifically mention the hazard of local run-off along the mitre. However, this hazard relates to surface erosion and, in turn, to climate-change effects, which have received a high priority ranking of 6.

Further guidance may be required on surface erosion, but international research is underway. Emphasis should be placed on increasing the awareness of inspecting engineers and designers to this hazard. This could be achieved with updates to existing key documents and/or by producing a practical checklist for inspections.

3.1.38 Surge in pipework

Definition

High or low transient pressure in pipework caused by operation of the system. This can result in catastrophic failure of the pipeline or equipment, or fatigue failure of the pipeline, supports or equipment.
Examples:

- A butterfly valve was used to replace a life-expired, in-line flow control valve. The butterfly valve slammed shut because of breakage. The resulting pressure surge caused failure of upstream pipework.
- Starting and stopping booster pumps on a pipeline several miles downstream of a dam caused a transient pressure surge, which burst the pipe in two places between the pumps and the dam and blew off an air valve at the dam.

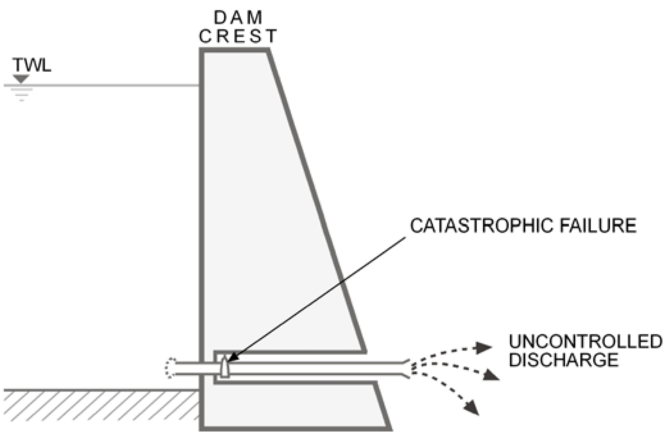

Figure 3.37 Surge in pipework.

CIRIA 170 gives comprehensive guidance on the design, operation, maintenance, monitoring and risks related to valves and pipework. Additional guidance is given in key references such as CIRIA 161, BR 363 and BR 303. A case study that involved an incident in Ogston reservoir is given in Hughes *et al*. (2004).

The questionnaire mentioned the need to update the current CIRIA 170 guide to pipes and valves. The workshop highlighted the need for further guidance on the operation of pipework.

Defra's research strategy concludes existing guidance on controls, valves and gates needs to be reviewed and updated (ranked 26).

The current study concludes existing guidance on controls, valves and gates needs updating based on recent international published research, but this is already identified in Defra's research strategy.

3.1.39 Corrosion

Definition

Oxidation of metal that reduces its properties:

- reduction in section thickness and strength;
- reduction in strength with no reduction in thickness;
- pitting of surfaces that permits leakage;
- pitting of surfaces that increases friction, which affects the performance of bearings and valve stems.

Corrosion in ancillary works such as pipes and valves is discussed in CIRIA 170. CIRIA 148 discusses oxidation of metallic components in relation to concrete dams. Academic references include Doyle *et al*. (2003) and many text books that discuss the process of corrosion in relation to civil engineering. With regards to general corrosion problems in many types of steel structures, Eurocode 3 is, perhaps, the most comprehensive. Several case studies are reviewed in CIRIA 170.

The questionnaire gave no indication of missing guidance about this topic. However, the workshop emphasised that CIRIA 170 does not provide practical guidance. For example, further information on the assessment of cast-iron pipes may help substantiate the case for re-lining of outlet pipes.

Defra's research strategy already concludes that existing guidance regarding controls, valves and gates need to be reviewed and updated, and this should include guidance on corrosion (ranked 22, 26 and 45). Reference should be made to Eurocode 3.

3.1.40 Failure of bywash channels

Definition

Bywash channels often have a bund of natural ground or fill that separates them from the reservoir and embankment dam. This bund may be narrow and susceptible to instability, deterioration and damage by animals, trees and erosion. The bywash itself may be susceptible to blockage by vegetation debris or sediments. Loss of bywash may result in additional loading on the spillway
Source: In part from BRE 363

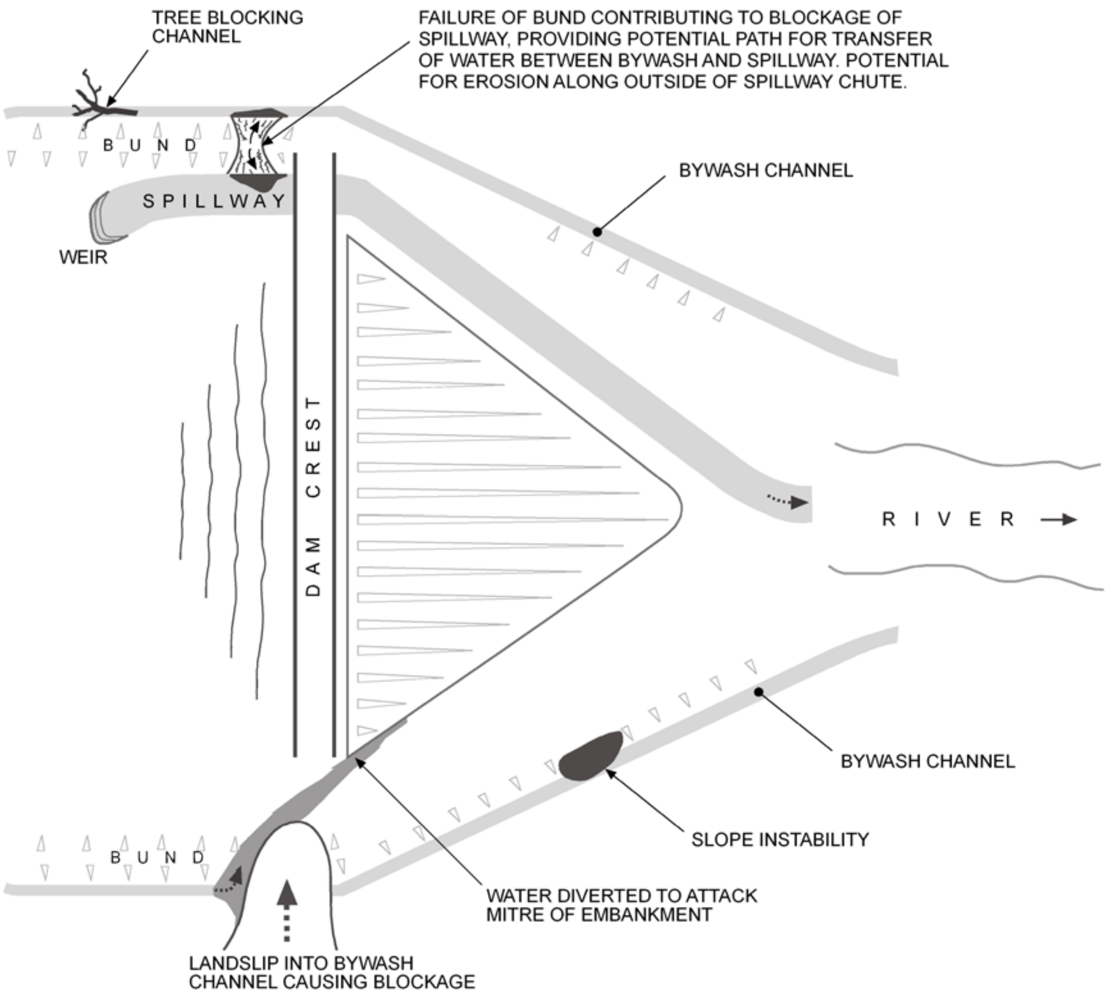

Figure 3.38 Failure of bywash channels.

Failure of bywash channels was raised in the workshop as a hazard to be considered if existing guidance is updated, as it does not currently cover this hazard.

This hazard was not raised in the questionnaire. However, it does closely relate to the failure of overflow works and surface erosion, so reference should be made to hazards such as those in Sections 3.1.15, 3.1.20 and 3.1.22.

The hazard of failure of bywash channels is not mentioned explicitly in Defra's research strategy. However, related subjects, such as the direct effects of climate change and overflow works, are given a high priority ranking.

It is concluded that the hazard of failure of bywash channels should be considered for further research and this could be incorporated into the project of Defra's strategy that relates to overflow works (project ranked 3). The hazard should also be taken into consideration when any of the existing key documents are updated.

3.1.41 Wave attack on upstream face

Definition

Wind-generated waves on the reservoir cause loading on the dam or wave wall. Waves can vary with location on the dam and can be concentrated by structures in the reservoir or trees that grow on the crest or upstream face.
Waves can cause erosion damage of the slope protection and structural damage to wave walls.

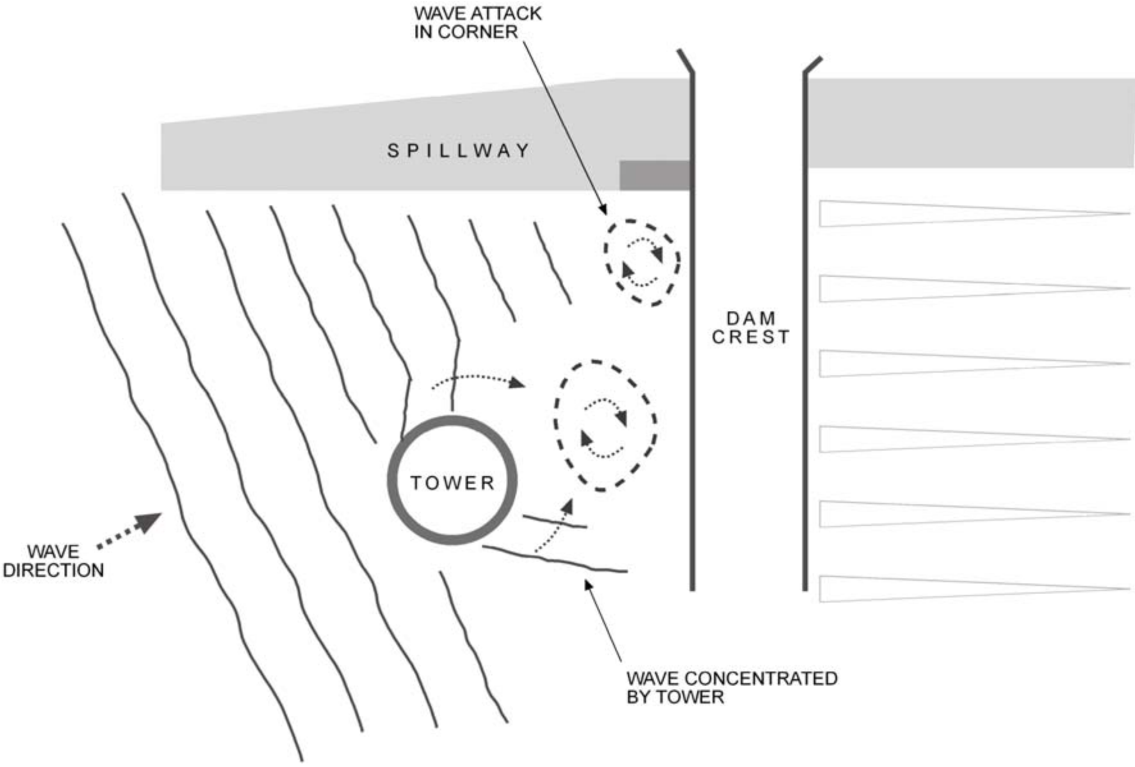

Figure 3.39 Wave attack on upstream face.

Comprehensive guidance is provided in BR 363, BR 303, CIRIA 161, ICOLD (1993c) and Environment Agency (2009c). Additional information on upstream slope protection is given in Besley *et al*. (1999), Bridle and Robertshaw (1994), Bramley and Hewlett (1988), Carlyle (1988), Horswill (1988), Penman (1984), Shave (1988) and Yarde *et al*. (1996). References related to coastal engineering include CIRIA 154, CIRIA 353 and Owen (1980). Case studies are investigated in Dempster and Lannen (2002), Dempster *et al*. (2004), Hay-Smith (1998) and Chanson and Aoki (2005).

Although a significant amount of guidance was identified, and weaknesses in knowledge were addressed in the workshop and supplemented by Professor Allsop of HR Wallingford (1985):

- wind-speed assessments are made with no consideration of the effects of local variations;
- wave-generation prediction methods display systematic errors in wave period;
- no account is normally taken of the diffraction effects of draw-off towers;
- stability of armouring is addressed by CIRIA, Civieltechnisch Centrum Uitvoering Research en Regelgeving (CUR), Centre d'études Techniques

Maritimes et Fluviales (CETMEF) Rock Manual (2007) and the Revetment Manual (McConnell, 1998), but gives over-optimistic prediction of stability of rip-rap slopes;
- wave-driven erosion of reservoir sides, particularly on initial impounding, generates sediment flushes and flotsam.

Further points were also made about the reliance on reeds to protect reservoir membranes, wave slop and wave wall. These are discussed in Sections 3.1.42 and 3.1.44.

The FLOODsite project (Task 4) reviews mechanisms of wave attack or physical erosion of the upstream face, such as grass, clay, rock armour and gabion protection. A review of subsoil erosion through block mats, concrete mattresses, gabions and geomembranes is also included, together with mechanisms of uplift and erosion of asphaltic or other types of revetments. All these mechanisms are given reliability or limit-state equations to be used in analysis.

The workshop also identified out-dated information in CIRIA 161 and drew attention to the ongoing research within the flood reservoir community. Such research on the effects and mechanisms of wave actions can be found in FLOODsite (Task 4), where reliability equations are available.

The Defra research strategy identified that wave-height predictions, wave-impact forces on wave walls and wave-wall protection required further guidance with a priority ranking of 38.

The current review identifies the need to update existing guidance on wave attack on the upstream face based on recent international published research, but this is already identified in Defra's research strategy.

3.1.42 Wave carry-over and wave slop (wave overtopping)

Definition

The water from the crest of waves that flows or is blown over the top of the dam in sufficient quantity to cause problems on the crest or the downstream face.
Source: Institution of Civil Engineers (1996)

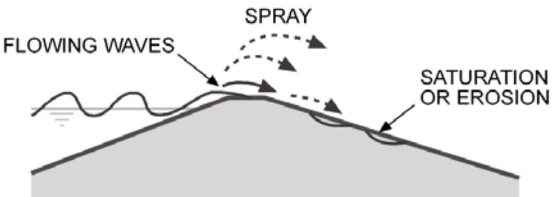

Figure 3.40 Wave carry-over and wave slop.

The subject is discussed in detail in *Floods and Reservoir Safety* (Institution of Civil Engineers, 1996), CIRIA 161, BR 363, Environment Agency (2009d) and several key papers and guides such as Besley (1999), Besley *et al*. (1999), Bridle (1994), Hewlett *et al*. (1987) and Yarde *et al*. (1996). Wave analysis has been studied extensively in coastal engineering and information can be obtained from the Meteorological Office in conjunction with the prediction methods, such as JONSWAP, that are reviewed in Owen (1988) and Allsop *et al*. (1985).

Research on the construction and design of seawalls was investigated by Owen (1980) and guidance is given in CIRIA 353. Case studies, such as the Breaclaich and Megget dams, are discussed in Dempster and Lannen (2002) and Hay-Smith (1998), respectively.

Erosion of the downstream face caused by wave carry-over or wave slop is explored in FLOODsite (Task 4) and reliability equations are available.

Although a significant amount of literature was identified, weaknesses in knowledge were addressed in the workshop and supplemented by Professor Allsop (Allsop *et al.* 2007), and include:

- The effect of wind speed on overtopping enhancement by spray was discussed by Pullen *et al.* (2008) for sea walls, but no methods are available for embankment dams.
- Guidance on the relationship between freeboard, run-up allowances and overtopping discharges has now been around for some time. More recent guidance can be found in the EurOtop manual (2007).
- Guidance on the erosion of the downstream face cause overtopping is outdated and predicted too pessimistically. Van der Meer (2007, 2008) discusses case studies involving sea dykes in Holland. Extended testing of embankment resistance is scheduled in Holland, Vietnam, Belgium and Germany during 2009–2010, and similar testing has been suggested to the Environment Agency for UK flood defences.

Defra’s research strategy identified that related subjects of wave-height predictions, wave-impact forces on wave walls and guidance on wave-wall protection needed further guidance with a priority ranking of 38.

In the context of Defra’s strategy, workshop and comments from senior members of the reservoir community, the current review identified the need to update existing guidance on wave carry-over and wave slop based on recent, international published research. Further research is required on the effect of wind speed on overtopping.

3.1.43 External threat that causes waves or damage

Definition

A single large wave caused in a reservoir by landslide, earthquake or failure of an upstream reservoir. The wave may overtop the crest of the dam and cause damage. The landslide itself may cause damage to structures.

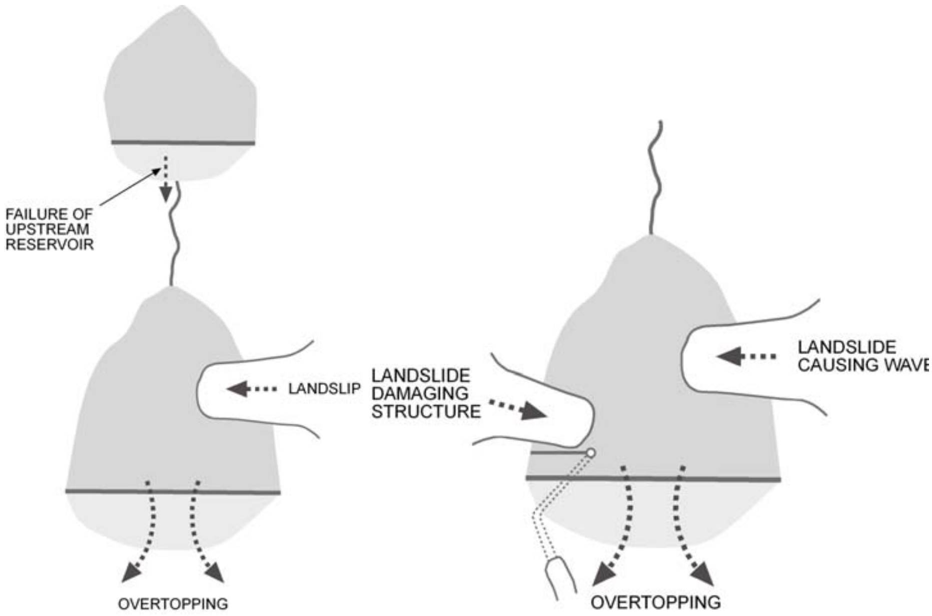

Figure 3.41 External threat that causes waves or damage.

Waves generated from earthquakes are discussed in BR 210, ICOLD (1986a, 1992) and Institution of Civil Engineers (1998). The case study of the infamous catastrophic failure of Vaiont reservoir is discussed in Hendron and Patten (1985) and relates to a single colossal wave that overtopped the dam as a result of a landslide into the reservoir, thought to be induced by a combination of factors. Another case study of Eigiau and Coedty dams in 1925, Walsh and Evans (1973) describe the failure of an upstream reservoir that generated overtopping of a downstream reservoir. This kind of cascade failure is also discussed in Amdal and Riise (2000) with regards to the Venemo dam in Norway. Catastrophic failure at Bold Venture reservoir in 1848 is described in Aighton (2003) and was caused by a flood-wave caused by an abnormal rain event. Dounias *et al*. (1996) published a paper on landslide reactivation at Evinos dam. A recent case study includes many landslide events that occurred at the Three Gorges Dam in China, reviewed in papers such as Xu *et al*. (2009) and Fourniadis *et al*. (2007a–2007c).

The questionnaire did not mention the hazard of wave or damage caused by external threat. The workshop emphasised the link between this hazard and risk analysis investigated in documents such as the QRA guide (Brown and Gosden, 2004) and FLOODsite (Tasks 2 and 7), but concluded that no further guidance is required.

The Defra research strategy does not identify the hazard of wave or damage caused by external threat as one that requires further guidance.

The current review concludes that, although further guidance does seem to be required, this is already addressed in the Defra strategy by linking modes of failure with risk analysis techniques such as event trees. Defra's strategy also highlights the indirect effect of climate change, which could lead to more landslides. Furthermore, this subject is addressed in the Foresight project (www.foresight.gov.uk) and concerns were made as to the generally increasing risk of landslides as a result of climate change. Research on this specific hazard may be considered a low priority in the UK, but the hazard should be taken into consideration in the studies on climate change.

3.1.44 Wave-wall inadequacy

Definition

- Insufficient height or extent to protect against waves during the design storm with concurrent wind speed.
- Inadequate strength to withstand the loading from waves.

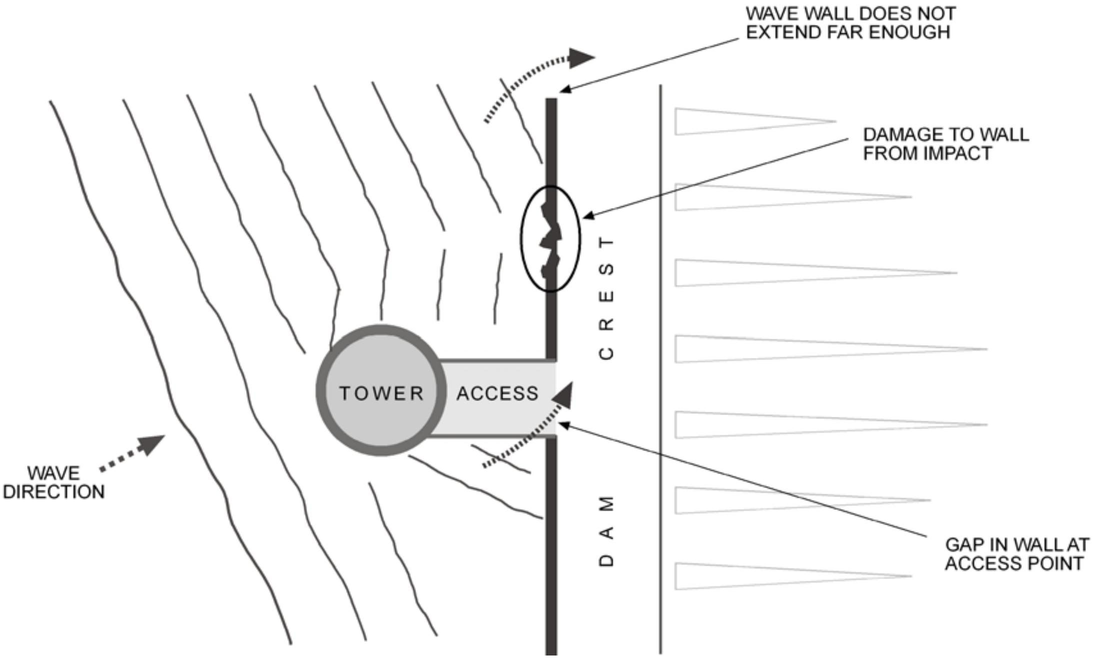

Figure 3.42 Inadequacy of wave wall.

Wave-wall design is covered in BR 363, Institution of Civil Engineers (1996) and CIRIA 154. Besley (1999) discusses the design and assessment of sea walls. Dempster and Lannen (2002) review wave-wall refurbishment works in Breaclaich dam. BS 6349 gives further guidance on the design of maritime structures in general.

Weaknesses in knowledge were addressed in the workshop and supplemented by Professor Allsop. It is suggested the design of various wave walls would fail rigorous checks with current knowledge. As these are of prime importance in preventing wave overtopping for little increase in cost, further research is deemed necessary.

Defra's research strategy identified that wave-height predictions, wave-impact forces on wave walls and guidance on wave-wall protection required further guidance with a priority ranking of 38.

The current review identifies the need for further research on wave-wall inadequacy, but this is already identified in Defra's strategy.

3.1.45 Crest fissuring or rutting

Definition

Deterioration of the crest through either drying out of the fill material, which results in cracking, and/or rutting caused by traffic. The effect of wetting in the winter and drying in the summer can exacerbate.

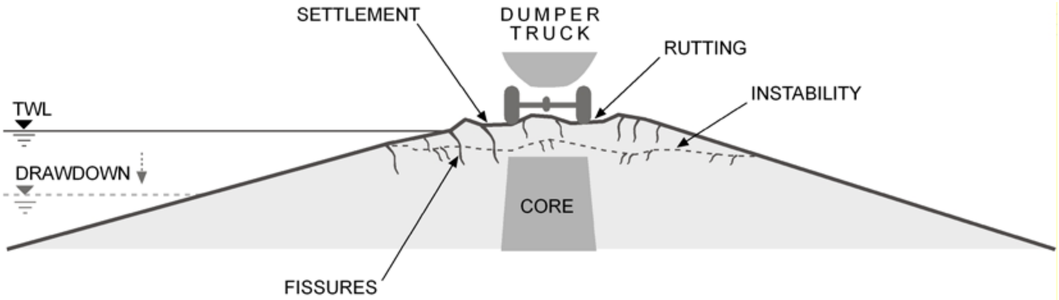

Figure 3.43 Crest fissuring or rutting.

Recent research within the FRMRC has produced a comprehensive guide relating to fissuring of flood embankments and is considered a key reference (FRMRC, 2007).

BRE (1996) makes general reference to desiccation in clay soils. Academic references on the subject of drying of the core include Kilby and Ridley (2006), Moffat (2002), Boden and Charles (1984), Watts (1904) and Bishop (1946). Rehabilitation of puddle-clay cores is discussed in St John *et al*. (1998) and Ray and Bulmer (1982).

The workshop concluded that further guidance is required and emphasised the relevance of this hazard to homogeneous embankments.

Defra's research strategy has not referred to this hazard as one that requires further research.

It is concluded here that further research is needed and existing guides, such as BR 363, should be updated, taking into account research conducted within the FRMRC. Emphasis should be made on the role of the inspecting engineer.

3.1.46 Controlled holding of water at a lower level

Definition

To control or maintain the water in the reservoir at a low level for an extended period for operational or hydrological reasons can lead to drying, shrinkage and cracking of a homogeneous clay embankment or clay core, which results in leakage paths when it is refilled.

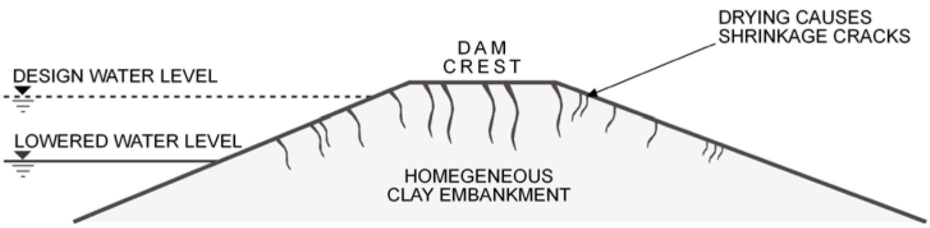

Figure 3.44 Controlled holding of water at a lower level.

Recent research within the FRMRC produced a comprehensive guide to the fissuring of flood embankments and is considered a key reference. Another general reference that relates to desiccation in clay soils is BRE (1996). Academic references on drying of the core include Kilby and Ridley (2006), Moffat (2002), Boden and Charles (1984), Watts (1904) and Bishop (1946). Rehabilitation of puddle-clay cores is discussed in St John *et al*. (1998) and Ray and Bulmer (1982).

A key case study on the drying of the core after a prolonged drawdown is given in the Environment Agency's database of serious dam incidents.

Defra's research strategy has not referred to this hazard as one that requires further research. However, it is concluded here that further guidance is needed and existing guides such as BR 363 should be updated according to research conducted within the FRMRC. Emphasis should be made on the role of the inspecting engineer.

3.1.47 Exceeding intended design loads in use of dam or ancillary structures

Definition

Deliberate or accidental act by a person that affects the ability of components of a dam to perform satisfactorily.
Examples:

- exceed crest-load restriction and so cause failure of a wave wall;
- removal of riprap, which causes concentrated wave erosion;
- replacement of a life-expired valve with one of unsuitable design;
- modification of a spillway that results in undesirable flow conditions.

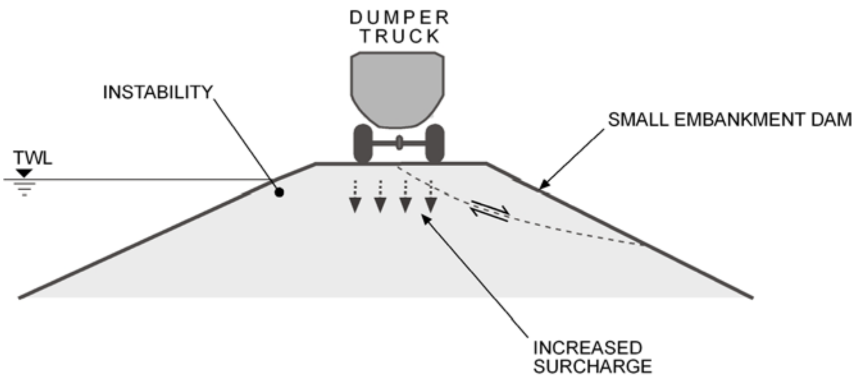

Figure 3.45 Design loads of dam or ancillary structures exceeded.

BR 363 and CIRIA 170 discuss this briefly and case studies are given in the recent Environment Agency *Post-incident report* (2009). Vandalism is discussed in CIRIA SP91. Anti-terrorism legislation is discussed in the Home Office (2004), but no direct reference is given to dams.

Exceeding the design loads of a dam or ancillary structure is a particular problem with small embankments and involves a large spectrum of modes of failure, such as crest problems or overall stability.

The questionnaire mentioned the topic as lacking sufficient guidance. The workshop highlighted the need to separate out the operator from third parties, and the requirement for general guidance on how to deal with the public.

This hazard has not been referred to in Defra's strategy.

Generic guidance on design loads would be difficult to produce. Further guidance on the relationship between dam owners, engineers and public would be useful to ensure design loads are not exceeded and this should include comment on use of the health-and-safety file for the reservoir, if available.

3.1.48 Earthquake loading

Definition

Earthquake loading on dams caused by seismic events, usually defined by a peak ground acceleration.
Seismic events cause a ground motion with shaking to which structures respond in different ways:

- the overall stability of the dam may be reduced;
- the shaking may cause settlement of embankment dams with reduced freeboard;
- ancillary structures may be damaged;
- foundation settlement may take place because of volume reduction or liquefaction.

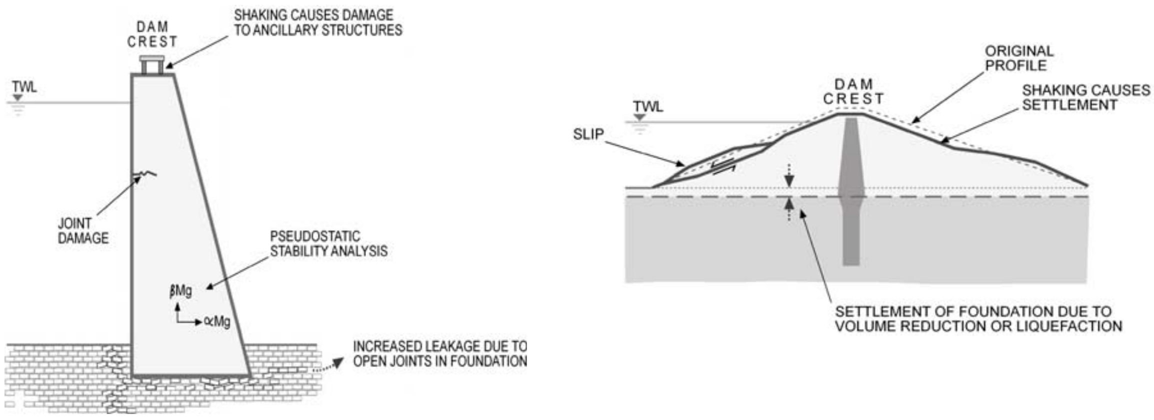

Figure 3.46 Earthquake loading.

Guidance on earthquake loading is given in BR 210, including an application note, ICOLD (1983b, 1986a, 1988, 1989c, 1995a, 1999, 2001a, 2002) and Institution of Civil Engineers (1998). Eurocode 8 gives general guidance on seismic design. Academic papers that discuss many aspects of seismic design for dams include Makdisi and Seed (1978), Swaisgood (1995), Daniell and Taylor (1994, 2000, 2002, 2003), Daniell *et al*. (1991), Feldman and Charlwood (2002), Dempster *et al*. (2002), King (1996), Swannell (1994, 1996), Taylor and Daniell (1998), Taylor *et al*. (1994), Gosschalk *et al*. (1994), Hinks *et al.* (2003a), Morison (2003 *et al*.), Rigby *et al*. (2002), Scott and Bommer (2002), Kennard and Mackay (1984), Hartford and Lou (1994), Knill (1975), Ballard and Lewin (1998), Reilly (2004) and Lubkowski and Duan (2001). Case studies are discussed in Claydon and Reilly (1996), Swannell (1996), Musson (1991), Mejia *et al*. (2002), Walters (1964) and Williams (1996).

The workshop concluded that no further research is required on earthquake loadings, which it considered to be well understood.

No further research or guidance is deemed necessary on earthquake loading. However, modifications to the current guidance should be made in accordance with Eurocode 7 and Eurocode 8 as to certain design aspects, such as factors of safety for slope stability.

3.2 Modes of failure

Modes of failure of dams are described in Sections 3.2.1–3.2.12. Arguably, those likely to be of main concern in the UK are catastrophic overtopping and dam breach.

3.2.1 Catastrophic overtopping

Definition

Uncontrolled flow over the dam crest.

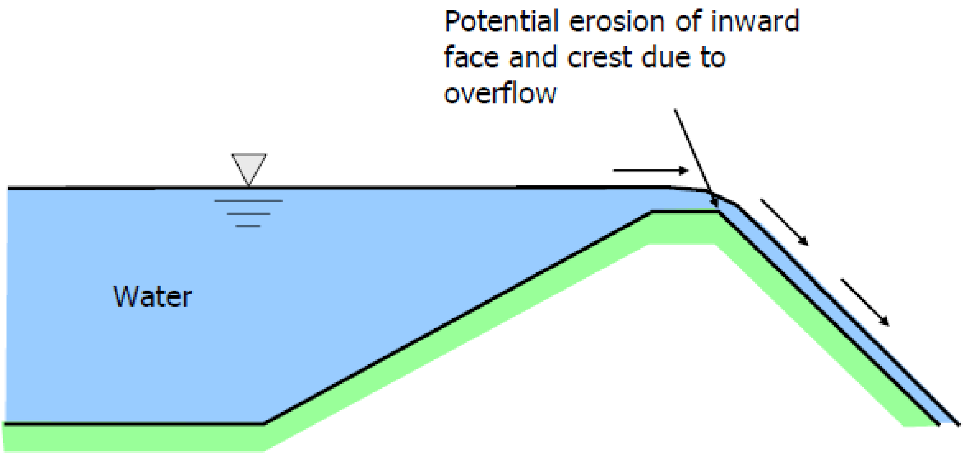

Figure 3.47 Catastrophic overtopping (Allsop, 2007).

3.2.2 Dam breach

Definition
Uncontrolled flow of water though the dam's main structure, which includes its foundation.

Figure 3.48 Dam breach (Morris, 2009b).

3.2.3 Foundation failure of concrete dam

Definition
Ultimate failure of concrete dam foundation or abutments because design loads or exceeded or through loss of foundation strength.

Figure 3.49 Foundation failure of concrete dam (Durham University).

3.2.4 Foundation failure of embankment dam

Definition
Ultimate failure of embankment dam foundations because design loads are exceeded or through loss of foundation strength.

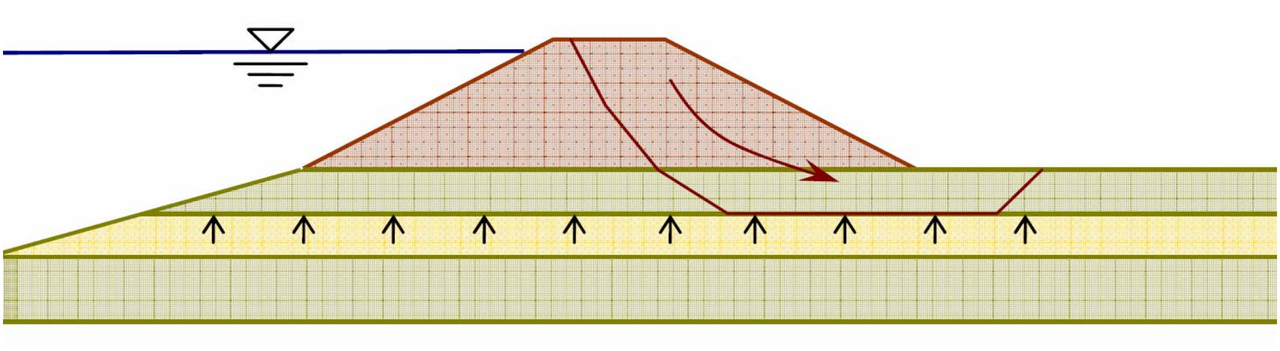

Figure 3.50 Foundation failure of embankment dam (Morris, 2009a).

3.2.5 Instability of concrete dam

Definition
Concrete dam slides or topples because design loads are exceeded.

Figure 3.51 Instability of concrete dam (Natural Resources Canada).

3.2.6 Instability of embankment dam

> **Definition**
>
> One or more slips occur within the embankment because design loads are exceeded or through a reduction in shear strength of embankment-fill materials over time.

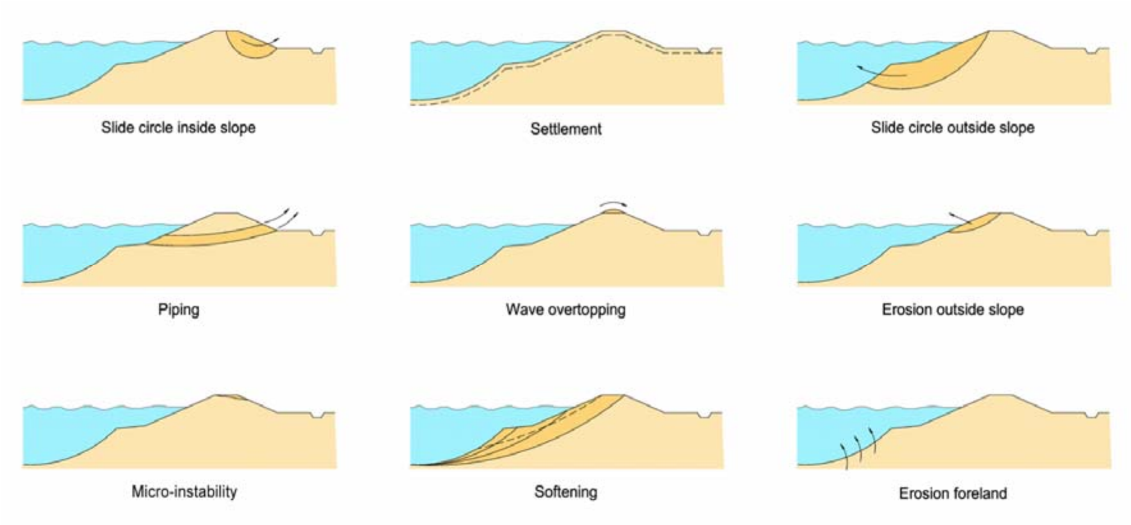

Figure 3.52 Instability of embankment dam (Environment Agency, 2007).

Figure 3.53 Instability of downstream shoulder of dam (North Carolina Department of Environment and Natural Resources, 2009).

3.2.7 Overflow failure

Definition

Overflow or spillway is unable to contain flow during flooding and uncontrolled flow results. Structural failure may occur.

Figure 3.54 Flood event of June 2005 that resulted spillway damage at Boltby reservoir (Walker, 2008).

3.2.8 Structural failure of concrete dam

Definition

Ultimate failure of concrete dam structure because design loads are exceeded and/or through deterioration over time.

Figure 3.55 Structural failure of concrete dam (England, 2009).

3.2.9 Structural failure of embankment dam (deterioration of core)

Definition
An increase in permeability and/or reduction in strength of core occurs over time, and results in ultimate failure of the embankment dam structure.

Figure 3.56 Muddy discharge downstream of dam as a result of increased seepage and internal erosion (North Carolina Department of Environment and Natural Resources, 2009).

3.2.10 Structural failure of embankment dam (load exceeded)

Definition
Ultimate failure of embankment dam structure because design loads are exceeded and/or through deterioration of embankment-fill materials over time.

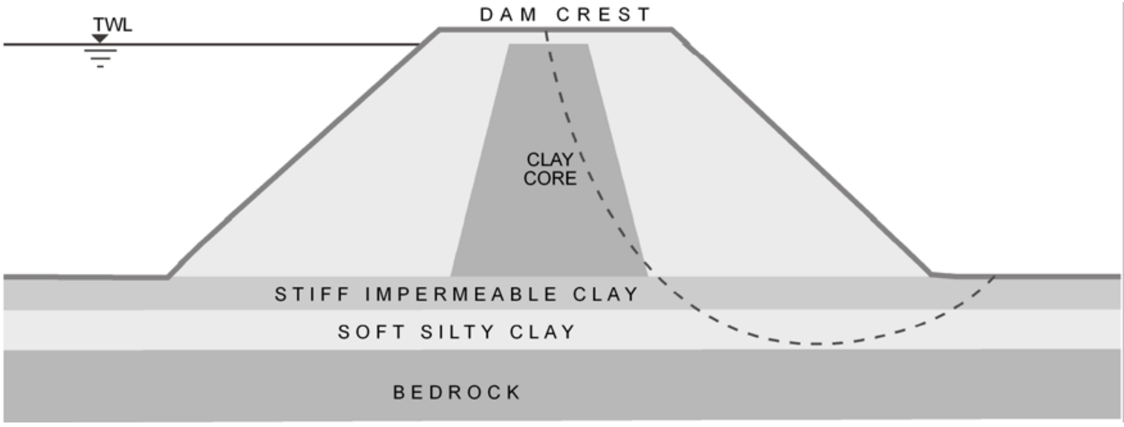

Figure 3.57 Structural failure of embankment dam (load exceeded).

3.2.11 Uncontrolled flow because of appurtenant works failure

Definition

Structural failure of one or more appurtenant works occurs because of a change in load conditions or deterioration of works over time that results in the uncontrolled release of water.

3.2.12 Uncontrolled seepage

Definition

Uncontrolled passage of water through, underneath or around a dam.

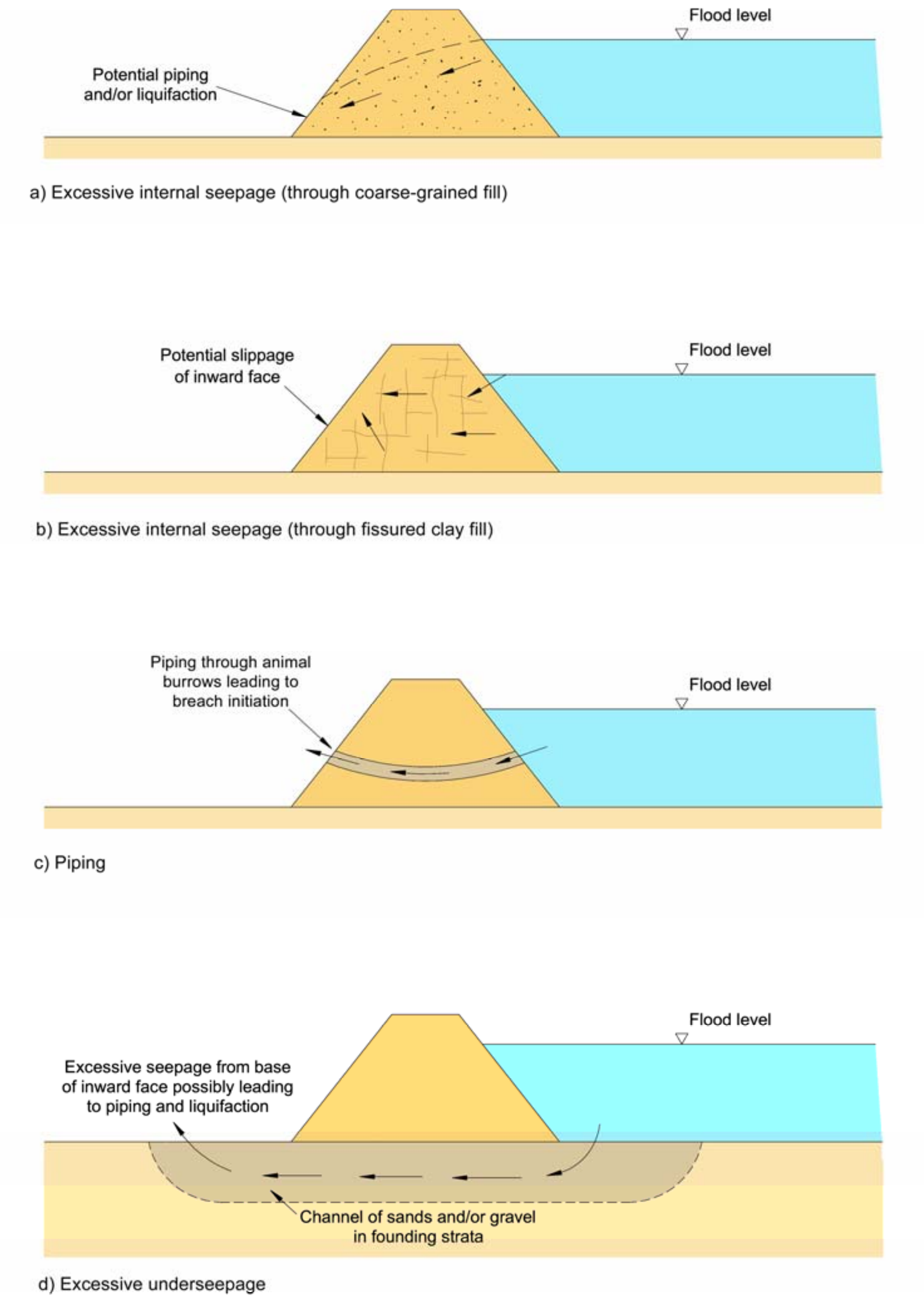

Figure 3.58 Uncontrolled seepage (Environment Agency, 2007).

3.3 Summary – modes of failure

In completing this scoping study it has become apparent that to understand the modes of failure, as defined in Table A.2, it is necessary to understand all potential hazards to a dam. These are defined in Section 3.1 above. Appendix B gives a brief summary of the findings of the scoping study in relation to each hazard.

The classification presented here took into account another classification of dam failure and serious incidents that have occurred during the past 200 years to reservoirs for 100 incidents (Tedd et al, 2010). Many more will have occurred, but included are those generally in the public domain and the major failures that involved loss of life. Although the sample of incidents is relatively small it is similar to distributions published by others (Charles 1986). The principal failure modes that are highlighted include internal erosion, instability, overtopping and spillway inadequacy, and failure of pipes and valves.

4 Monitoring and measuring techniques

Discussions in the workshop focused on the usefulness of techniques and the gaps in our knowledge. Results of the discussions are included in the following sections.

The general consensus was that guidance exists on monitoring and measuring techniques. The key documents are:

- *Investigating embankment dams: a guide to the identification and repair of defects*, Building Research Establishment Report BR 303 (Charles *et al*., 1996);
- *An engineering guide to the safety of embankment dams in the United Kingdom*, Second Edition, Building Research Establishment Report BR 363 (Johnston *et al*., 1999);
- *Engineering guide to the safety of concrete and masonry dam structures in the United Kingdom*, CIRIA Report 148 (Kennard *et al*., 1996).

The consultations carried out as part of this scoping study have indicated that these may be out of date and, in some cases, it is not clear what techniques are most appropriate for dams and what the results mean.

4.1 Monitoring and measuring techniques for different indicators

The techniques that can be used to check for the indicators defined in Table A.3 (Appendix A) were considered in the scoping study and are discussed below. These are categorised in terms of:

- deformations
- pore-water pressures
- earth pressure in core
- seepage and leakage
- structural integrity
- other.

A summary of the usefulness of each of the techniques is provided in Table A.4.

There was some discussion in the course of the scoping study about what monitoring actually is. The consensus was that it should include the use of equipment or techniques to monitor performance. Although monitoring equipment may be installed initially as part of an investigation, the investigation itself was regarded as separate to the monitoring regime for the purposes of this study. The importance of surveillance by experienced engineers was noted throughout the discussions. This is probably the most common way to monitor the performance of a dam, but it generally includes a number of different techniques (see below). Surveillance was considered when the recommendations in Section 6 were made.

At the time of issue of this report, a key project had just been commissioned by Centre for Energy Advancement through Technological Information International (CEATI) with the Dam Safety Interest Group (DSIG) on the development of a ‘performance monitoring and data analysis management best practices report'. This will aim to summarise the equipment available to monitor:

- deformations
- pore-water pressure and total stress
- forces, strains and cracks
- flow and turbidity
- vibrations and accelerations.

It is therefore recommended that the findings of the CEATI–DSIG study be taken into consideration in any recommendations made in this scoping study and that the above headings are considered as replacements for those used in Table A.3 and Table A.4, if appropriate.

Importantly, it is extremely unlikely that monitoring of instrumentation will be able to warn of an immediate impending incident or failure in an existing dam, although there is some debate as to whether or not internet-based monitoring and alert systems may allow this. Instrumentation has, however, been used to confirm that long-term performance is satisfactory and that the structure remains in a safe condition. It can aid understanding of possible mechanisms of deterioration, such that appropriate remedial measures can be taken to avoid a potential incident. By monitoring some facet of behaviour, such as embankment settlement, it is possible to predict future rate and magnitude of settlement in the long term. Monitoring of deformation and pore-water pressures is used to target appropriate investigations or remedial works. Appropriate instrumentation allows quantification of behaviour.

Not all hazards can be monitored by instrumentation and for some surveillance and/or measurement is required, or simply an awareness of the potential impact. Instrumentation is not a substitute for frequent, vigilant surveillance, which came across very clearly in the consultation process. Measurements are usually discontinuous in space and time. Data from instrumentation is not comprehensive and the most adverse circumstances may not be recorded. Instruments may malfunction and give no measurement, or worse give erroneous readings, so it is important in the first instance to have an understanding of the likely mechanisms of behaviour of a structure.

The monitoring and measuring techniques presented in Table A.4 were identified through a literature search and consultation with the reservoir community (Section 1.1.2). These techniques are discussed in this section, along with general comments on the monitoring of threats.

4.2 Methods to monitor and measure embankment dams

4.2.1 Commonly used methods

Methods identified in responses to the questionnaire as being worthwhile are:

- regular surveillance
- seepage-flow monitoring
- visual, crest levelling
- telemetry
- piezometers
- inclinometers
- water line
- rainfall monitoring.

Several answers noted that all methods are good as long as readings are taken regularly and understood.

In summary, considerable guidance on commonly used methods is available in BR 303. The methods themselves are generally well understood by industry, but there is often a lack of understanding by individuals about what needs to be monitored and which methods to use. Further information would be useful on certain aspects and details are provided in the subsequent sections. There is merit in obtaining data on what type of instrumentation is used in old dams for the Environment Agency database (Defra strategy project ranked 5).

4.2.2 Deformations

Workshop delegates considered crest levelling and sighting rods to be the most useful and widely used techniques, with a precise survey of the whole embankment used occasionally. Remote sensing, LiDAR and aerial photographs are used rarely. However, it was recognised that these techniques are used more frequently on flood embankments and some lessons could be learned on reservoirs. In addition, it was thought that these geophysical techniques could be useful, but were poorly understood, and if guidance was updated it would be useful to include these. In particular, ground-penetrating radar (GPR) and electromagnetic surveys were mentioned.

Methods to monitor surface deformations are described in Sections 4.2.2.1–4.2.2.5.

The often complex instrumentation required to measure internal displacement is installed at relatively few existing dams. Valuable information on horizontal and vertical displacement has been obtained from instruments installed during construction and, where such installations exist, it is worthwhile to incorporate them into the routine monitoring system.

Methods to monitor internal deformations are described below in Sections 4.2.2.6–4.2.2.9.

4.2.2.1 Crest levelling

For most dams, measurements of surface displacements are limited to settlement of the crest using precise levelling and surveying techniques. Routine monitoring of embankment deformations is important to assess long-term behaviour, evaluate safety and quantify potential hazards. Accuracies of 1–2 mm can be achieved using levelling. When ‘total station’ instruments are used, accuracies can increase significantly. This is a low-cost exercise compared with measuring movements in plan. The problem with crest levelling is to establish reference benchmarks that do not move.

4.2.2.2 Precise surveying – whole embankment

Deformation of embankments is an important indicator of field performance. Settlement or heave of dam crests is the most common parameter monitored or measured.

Horizontal displacements near the toe of an embankment are particularly useful where the slope stability is of concern. Horizontal displacements are not measured frequently at the crest or on the slopes.

A reasonably wide choice of instrumentation, measurement systems and surveying techniques is available (theodolites, optical levels, photogrammetry and electronic distance measurement).

Modern survey equipment can be linked to computers either directly or remotely, which provides rapid and reliable measurements. Accuracies are usually within a few millimetres, but are dependent on a variety of factors such as type of instrument, repeatability of instrument positions, long-term stability of reference points, competence of survey staff and meteorological conditions during the measurements.

Survey equipment can also be set up as permanent geodetic networks, such as at Queen Mother Reservoir where a network was set up to measure surface movement.

4.2.2.3 Remote sensing – satellite, LiDAR, aerial photos

Modern satellite monitoring technologies with application for deformation monitoring include global positioning systems (GPS) and permanent scatterer synthetic aperture radar interferometry (PS InSAR).

The use of GPS in day-to-day life has increased rapidly; accuracies have also improved. GPS can facilitate automatic monitoring of embankments by establishing permanent stations. Accuracies to a millimetre or less can be achieved. The degree of precision, however, is dependent on dam location, as satellite links are affected by topography and vegetation. GPS is relatively expensive, with high costs associated with both the receivers and data processing. Automated, robotic total-station measurements controlled by established telemetry systems, such as Geomos, may be a less expensive option (www.leica-geosystems.com).

The latest PS InSAR satellite monitoring equipment is capable of detecting the movement of embankments very accurately; however, it depends on detecting 'scatterers' in the radar scene, which tend to be hard features, such as concrete edges, rather than soft features, such as grass-covered earth. It is also used to detect vertical rather than horizontal movements, and so does not necessarily provide all the information required. The resolution of the SAR data is critical. Infoterra carried out some preliminary testing on data from the TerraSAR-X satellite. This year there were developments with acquiring cost-effective higher (1 mm) resolution SAR data from airborne platforms (see www.metasensing.com). Currently, in the UK PS InSAR is only used on one reservoir (Crichton, 2007).

LiDAR can be used to capture rapidly the geometry of complex hydraulic structures in a high-quality, digital format using terrestrial laser scanning data-acquisition techniques. There is evidence for the use of high-resolution LiDAR to monitor ground-movement, stability of river banks and embankments, and for coastal monitoring, where different geometric surfaces are generated from the data over a period of time. Applications to monitor reservoir embankments appear to be limited; this is likely to be an area for further R&D.

4.2.2.4 Sighting rods

Sighting rods have long-standing application in engineering as a method to determine straight lines, reference points and establish the correct geometry for engineering structures. Nowadays, they are more likely to be used in conjunction with modern survey equipment, such as levels and theodolites, to determine deformations in a structure such as a dam.

4.2.2.5 Other

Additional monitoring techniques include laser scanners combined with digital cameras, which are being developed and refined. According to Boavida *et al.* (2008), the use of such combined terrestrial imaging systems provides accurate and very dense three-dimensional numerical models, as well as spatially continuous, high-resolution red-green-blue (RGB) information of objects such as embankments. These techniques provide a huge amount of geometric and radiometric well-structured data in a short period of time. As yet, there is no evidence of real-life application of such techniques for dam and embankment monitoring, although there is much potential. The shape of the earth embankment at Cheshunt North Reservoir has been monitored since 2002 using total-station observations, so research to compare total station and laser scanning techniques at this site may be useful (see Section 6.4).

Boavida *et al.* (2008) found that, with regards to earth or embankment dam monitoring, sub-centimetre positional accuracy was achieved. However, it is expected that the accuracy will improve with advances in laser technology.

Crack meters and joint meters can be used to measure deformations. They include displacement transducers to measure one-dimensional displacement between two points that are experiencing separation, or sometimes closure. The devices were found to be robust, reliable, accurate and easy to install and read. They are typically electrically operated and can facilitate continuous, remote monitoring in real time. This can be useful for relating movement to environmental factors. Three-axis versions of the equipment are available and capable of taking orthogonal movement measurements.

4.2.2.6 Electro-levels

Electro-levels are a type of transducer within electronic tilt-meters that measure the degree of tilt monitored by the sensors in the tilt-meter. The use of electro-levels in existing dams is limited, but they were used to monitor movement during conducted and first filling at dams in the UK and overseas. Specialist contractors are required to installation and monitoring. They could be linked to an alarm system, as in other civil engineering structures. Although based on an electrical system their long-term reliability can be good, with reliable measurements for over 10 years. They can be used to measure movement remotely, but there is a low level of knowledge and guidance is probably required.

4.2.2.7 Inclinometers

Inclinometers comprise tubes, which are installed in boreholes, and reading devices, which are either lowered into the tubes to take readings or integrated within the tubing. They are installed at a limited number of existing dams where there are concerns about continuing movements. The data provide confidence that the dam is behaving satisfactorily. Inclinometers are potentially useful for monitoring, but there are concerns over repeatability and precision and they could pose more questions than answers.

Furthermore, inclinometers may be expensive to install and monitor.

4.2.2.8 Magnet settlement gauges

Magnet settlement gauges, also known as magnet extensometers, are installed in vertical boreholes to measure settlement at different depths. With the appropriate equipment accuracies of 1 mm can be achieved. The long-term reliability is good. Where surface settlement is measured or observed they are used to determine the location of the settlement. This proved very valuable in a study of the effect of drawdown settlements at an apparent sinkhole (Tedd et al. 2002). The system is essentially mechanical and, with care, measurement of better than 1 mm accuracy can be achieved. The longevity of the system is good, with observations taken at some sites for over 10 years.

Extensometers are considered useful during construction, but not particularly helpful for routine monitoring.

4.2.2.9 Slip indicators

Slip indicators are simple installations used to estimate the level at which a (suspected) discrete lateral displacement, such as a shear surface, occurs. As the name suggests, they provide an idea of the upper and lower bounds of lateral displacements and are not considered highly accurate. As a result, slip indicators are useful to determine the existence of a problem where it is suspected, but they are not used extensively for routine monitoring.

4.2.2.10 Summary

In summary, methods to monitor and measure deformations are reasonably well documented, with considerable guidance available in BR 303. However a number of techniques are used more widely on flood embankments from which lessons could be learned.

It would be useful to update the BRE report, particularly with remote sensing techniques, LiDAR and geophysical techniques such as GPR and electromagnetic surveys. However, the Defra research strategy already includes for a chapter on monitoring and measuring methods for embankment dams in a guide (ranked 9) and publication of a guide to instrumentation and monitoring (ranked 10). Therefore, the BRE report could be used as a basis, with information updated in accordance with this scoping study.

Additional projects identified in the Defra strategy should also take into consideration updated information. These projects relate to inspection and monitoring of tunnels (ranked 13) and guides on embankment dams (ranked 18 and 34).

4.2.3 Pore-water pressures

To evaluate safety, pore-water pressure is often the most important parameter to measure in an embankment dam. The measurement of pore pressure is important to determine the location of the phreatic surface and the overall pattern of the seepage through the embankment. Pore pressures in the embankment shoulders and foundations can be used in effective stress analyses limit equilibrium to compute factors of safety for the embankment slopes. Piezometers in the upstream shoulder of an embankment provide information to assess stability during rapid drawdown. Pore pressures in the central clay core and downstream fill can indicate the effectiveness of the core or cut-off. Piezometers can also be used to obtain parameters that contribute to understanding the behaviour of the dam:

- vulnerability of a central puddle-clay core to hydraulic fracture can be determined by critical pressure tests using standpipe piezometers installed in the clay;
- the permeability of the fill can be measured using standpipe piezometers.

This information can be used to assess the:

- upstream fill, which can provide information to assess upstream slope stability during rapid drawdown, and whether the full reservoir head will act on the core and therefore indicate whether drawdown settlement will occur;
- central clay core to determine the effectiveness of the clay core but, like all point-type data, it will provide localised information only;
- downstream fill to determine the filter properties using the perfect filter criterion proposed by Vaughan and Soares (1982).

Discussions in the workshop confirmed that standpipe piezometers were the most widely used technique, with more sophisticated pneumatic and vibrating wire techniques used less often. There was a lack of understanding of what to do with the data and why it was being collected. Information on the cost, reliability and effectiveness of all these techniques was considered something that would be useful.

4.2.3.1 Hydraulic piezometers

Hydraulic piezometers are generally installed during construction of new dams, rather than installed in existing ones. They are suitable for remote reading and provide long term reliability. They can also be used for critical pressure tests.

Their use in existing dams is limited by the requirement for the tubing not to be more than 5 m above the piezometric level.

4.2.3.2 Pneumatic and vibrating wire piezometers

Both types have rarely been installed in existing embankment dams in the UK. Their main advantage is that they have a rapid response time provided the stone and piezometers are properly de-aired. These piezometers have been used in the upstream shoulders of dams when investigating slope instability. Although specialist de-airable piezometers do exist, most types cannot be de-aired and should not be installed in partially saturated soils.

Pneumatic piezometers are relatively cheap and easy to install and require no correction for the differences in elevation between the readout unit and the tip of the piezometer.

The installation of the vibrating wire piezometer is similar to the pneumatic, but the instrument itself is much more expensive than the pneumatic. It is stable in the long-term, although care has to be taken to set them up for a required range of sensitivity.

Use of vibrating wire piezometers is more common outside of the UK.

4.2.3.3 Standpipe piezometers

Standpipe piezometers are the most common type of piezometer installed in existing dams because they are relatively cheap, simple to install, easy to read and their long term performance is usually good. Generally their use is restricted to the core and downstream fill, however they have been installed upstream of the central core either by using angled borehole from the crest or terminating the top of the standpipe above TWL.

Standpipe piezometers respond slowly to changes in pore water pressure and therefore are more suited monitoring situations where to long-term observations are required.

4.2.3.3 *Summary*

Information on types of piezometer and their use to measure pore-water pressures is available within the geotechnical community. However, the consultation process revealed that a report which provides details of the alternative types of piezometer available would be useful to the reservoir community. There is also a requirement to identify the reasons for collecting data and what the results mean.

The Defra research strategy already includes for a chapter on monitoring and measuring methods for embankment dams in a guide (ranked 9) and publication of a guide to instrumentation and monitoring (ranked 10). Therefore, it is recommended that these projects take into consideration the findings of this scoping study.

Additional projects identified in the Defra strategy should also take into account updated information. These projects relate to the inspection and monitoring of tunnels (ranked 13) and guides on embankment dams (ranked 18 and 34).

4.2.4 Earth pressure in cores

Where hydraulic fracture is suspected in existing dams as a mechanism that has initiated leakage through a core, various methods are available to investigate the earth pressures in the core. Provided the minimum total-earth pressure exceeds the reservoir pressure, hydraulic fracture should not occur. Methods include push-in pressure cells, critical pressure tests and various *in situ* testing methods such as the pressuremeter test.

The workshop delegates considered measurement of earth pressure to be non-routine and rarely used. Techniques are often used in construction, rather than to monitor existing structures. However, given the on-going research on internal erosion, this may be something that requires greater understanding in the future.

4.2.4.1 *Critical pressure test*

Critical pressure tests are carried out in piezometers and provide an indication of the local stresses.

The test is considered less reliable than others, but is nevertheless useful in particular circumstances – measurements can be made with piezometers already installed for other purposes, which means little expense. Furthermore, the test is quite simple if applied to a standpipe piezometer.

The test has limited application, being suitable only for clay soils. The relationship between critical pressure as determined by the test and *in-situ* pressure is and has been a matter of debate (Charles *et al.*, 1996).

4.2.4.2 *Pressuremeter and dilatometer tests*

Both the pressuremeter and flat dilatometer are profiling tools that have been used to measure stresses in puddle-clay cores. However, although both tests may find some application in embankment monitoring they are not used routinely for this purpose, and other tests are likely to be considered first for a variety of reasons, such as lack of continuity in the measurement profile.

Details of the methods are given in BR 303.

4.2.4.3 Push-in spade cells

These cells, probably more than any other instrument, require care, time and experience during their installation, maintenance, observation and interpretation. They were developed as a research tool by BRE in the early 1980s to measure total horizontal stress in puddle-clay core to investigate vulnerability to hydraulic fracture. They are only really suitable for use in puddle-clay cores that have a low strength, although they have been installed on one rolled-clay core dam. They are installed at some 14 dams and recent studies (Watts *et al.*, 2004) demonstrating their long-term reliability and value. Long-term monitoring is currently (2009) being carried out on dams belonging to two water companies.

Studies show that earth pressures in the puddle-clay core are generally above the reservoir head. Observations at a number of reservoirs show that reservoir refilling after a major drawdown is a critical time for hydraulic fracture. The stress conditions in narrow clay cut-offs tend to be more adverse than in the clay cores in the embankments. Measurements have been used to control the operation of some reservoirs, but meaningful observations are very unlikely. Push-in spade cells are not used routinely and cannot be bought off the shelf and installed by inexperienced investigators.

4.2.4.4 Summary

In summary, information on the measurement of earth pressure in the core is not well understood or used. Although it is something normally considered during construction, rather than to monitor an existing structure, it will be worthwhile to consider whether or not greater research is required as information on internal erosion becomes available (Defra project ranked number 1).

4.2.5 Seepage and leakage

The purpose of seepage and leakage investigations is to establish the source and volume of any flows through the dam, or around a dam through its foundations or abutments, and to investigate any damage that may be caused by the flows. Issuing water may not be through the dam, but may still present an instability problem for the downstream slope.

This is an area in which workshop delegates felt monitoring techniques should be focused. The simplest techniques are used most frequently, including inspection of chambers, use of a jug and stopwatch and V-notch weirs. It was recognised that detection of leaks is complex and difficult. Uses of some of the more complex techniques, including controlled source audiofrequency domain magnetics (CS-AFDM) and other geophysical methods, were considered worth further research. Understanding seepage issues is likely to become more important as research on internal erosion develops.

General methods to detect seepage and leakage are described in Sections 4.2.5.1–4.2.5.7 and techniques to detect zonal leakage are described in Sections 4.2.5.8–4.2.5.10.

4.2.5.1 Jug or bucket and stopwatch

This method is applied where no measuring facilities are installed and provides simple guidance on flow rates by using a stopwatch to determine the time taken to fill a container, such as a jug or bucket. As with a V-notch weir (Section 4.2.5.7), readings are taken to establish a pattern, and subsequently any deviations from that pattern are taken to indicate a problem.

4.2.5.2 Chamber with sump or settlement tank

Monitoring chambers are usually permanent monitoring installations and may contain a flow-measurement device, such as a V-notch weir, and a sump to collect sediment or other materials contained in the flows that may signify erosion from the dam. Analysis is carried out on the sediment to determine the potential source, pathways and rate of erosion.

Sediment-monitoring chambers can provide guidance on the normal routine of the dam, presence or absence of bacterial floc and potential sediment problems.

Further guidance on this data may be useful as research on internal erosion progresses.

4.2.5.3 Divining rods

The use of divining rods or the technique called dowsing is generally widely disputed. However, a paper published in the *Journal of Scientific Exploration* (Betz, 1995) states that in a series of experiments it was possible to locate small water-bearing aquifers with typically low yields.

The lack of agreement on whether the method actually works presents particular problems for monitoring leakage in dams and it is unlikely to be a serious choice. The workshop participants felt that the method was used ‘very occasionally’.

4.2.5.4 Tracers and/or chemical analysis

The use of tracers has helped to identify the source and location of issuing water at a number of dams. Leakage at reservoirs is investigated using chemicals, dyes and bacteriophages. Details on the various methods are given in Appendix A of BR 303.

Chemical analysis is used to identify the source of the issuing water and the origin of any suspended material. Chemical analysis is also used to establish whether chemical degradation of the material occurs within the embankment.

4.2.5.5 Observation wells

Observation wells are devices with no sub-surface seals (as opposed to piezometers). They do not require expert knowledge to install and are inexpensive. Typically, they are located downstream of a reservoir and are monitored for unexplained changes in water level, which may signify leakage and/or seepage through a dam.

They can also be used with tracer tests, in which the presence of a tracer or amount of time before a tracer is detected in an observation well can indicate flow paths and flow rates.

Observation wells can also be used to measure pore-water pressure within an embankment, but are generally considered unsuitable for this purpose.

4.2.5.6 Underdrain flows

Many dams in the UK are constructed with an underdrain system beneath the dam, which consists of collector trench drains that discharge into individual or collective manholes at the downstream toe of the dam.

Section 9 and Appendix A of BR 303 contain several examples from the UK that highlight the importance of underdrains in alerting engineers to the existence of a problem and, in tandem with other measures (such as drawing down the reservoir or use of tracers), determining the location of the problem.

4.2.5.7 V-notch weirs

Flow measurements are commonly made using V-notch weirs in which the depth of flow is recorded manually. Occasionally, remote automatic monitoring methods are used (Carter *et al.*, 2000). It is essential to record rainfall and reservoir level to assess the results. Relatively small reservoir drawdown close to the TWL of many reservoirs has a dramatic effect on flow rates that issue onto the downstream slopes.

Turbidity or suspended particles that indicate internal erosion can be measured in a sample or collected in a sediment trap.

4.2.5.8 Controlled source audiofrequency domain magnetics

CS-AFDM is a new method to identify leakage location through embankment dams. The method depends on the transformer theory in which two coils in close proximity can be electromagnetically coupled. During the investigation, more than 5000 readings are taken every four seconds. Five sites were investigated in the UK, two of which are described by Kofoed *et al.* (2008). Advantages of the method are that it is quick, non-intrusive and provides good horizontal accuracy.

However, there is only one provider, Willowstick Technologies (2007), who hold the patent, which is expensive.

4.2.5.9 Resistivity

Electrical resistivity is used for soil profiling and can be related to soil properties such as moisture content, degree of saturation, permeability and salinity (Kalinski and Kelly, 1993, in BR 303). However, it is only reliable where simple stratification occurs and can give serious inaccuracies with more complex stratification (Charles *et al.*, 1996).

The use of resistivity (and other geophysics methods) as the sole method to monitor dams is not recommended because the results on their own may be misleading. Geophysics techniques in general require careful correlation with borehole data and if used to measure soil properties, the measured geophysical properties must be correlated with the static properties that usually control the behaviour of the embankment (Johnston *et al.*, 1999).

4.2.5.10 Temperature

Ground-temperature measurements successfully located leakage paths within earth embankments at a number of dams in the UK (Dutton *et al.,* 2002, Andrews *et al.*, 2000). The theory behind the technique is described by Dornstadter (1997) and developments of the method by Dornstadter *et al.* (2006). The technique relies on the different seasonal temperatures within the ground and surface waters and the effect that water, percolating through the ground, has on its temperature. To locate the leakage path, the ground temperatures within the embankment are determined by temperature sensors lowered into hollow probes of small diameter and generally 10–20 m apart.

A leakage-detection system that uses fibre-optic cable cables to detect temperature was built into Winscar dam between the existing asphaltic membrane and the new polyvinylchloride membrane (Carter *et al.*, 2002).

4.2.5.11 Summary

The methods used to monitor seepage and leakage were identified as worth further research and guidance. Some of the more complex techniques, including CS-AFDMs and geophysical techniques, are considered worthy of inclusion in updated guidance, ideally with case studies. Further research may be justified in future, depending on the results of current research on seepage and internal erosion.

The Defra research strategy already includes for a chapter on monitoring and measuring methods for embankment dams in a guide (ranked 9) and publication of a guide to instrumentation and monitoring (ranked 10). Therefore, it is recommended that these projects take into consideration the findings of this scoping study.

Additional projects identified in the Defra strategy should also take into consideration updated information. These projects relate to inspection and monitoring of tunnels (ranked 13) and guides on embankment dams (ranked 18 and 34).

4.2.6 Structural integrity

The workshop delegates highlighted the importance of surveillance and the use of basic techniques to assess structural integrity. These include frequent use of crack meters and tell-tales, hammer tapping and inspection for algal growth or movement of mortar across gaps. Although these are useful techniques, they do not cover all the hazards identified in this scoping study and further research is required.

4.2.6.1 Hammer tap and chains

This method requires a geologist’s pick or similar hammer to tap concrete and listen for changes in pitch, which provide clues to the condition of the concrete. The method is applied to structures such as draw-off towers, conduits or localised areas on the monolith where problems are suspected, such as around cracks, and is applicable during an inspection to provide on-the-spot assessment.

Chains could be used in a similar manner to hammer taps, by dragging across a concrete surface and listening for changes in the sound produced.

4.2.6.2 Crack meters and tell-tales

Tell-tales are simple devices used to measure cracking in masonry or concrete over long periods of time. Two main types – plate and pin – are in use. Plate tell-tales are susceptible to vandalism and are less accurate. Accuracies of within 0.1 mm can be achieved with pin tell-tales, which are also less likely to be vandalised.

The development of cracks in concrete and masonry or concrete structures does not occur at a rate detectable in the short term; therefore the above methods of monitoring are only suitable for the long term.

4.2.6.3 Pendulum in valve tower

These have been installed in some draw-off towers and in concrete and/or masonry dams and are considered to be very reliable (Kennard *et al.*, 1996a). They can last for the lifetime of a dam and require little or no maintenance. They can also be designed to allow for automated monitoring. Pendulums are considered particularly useful as a means of visual inspection to determine whether deformation is occurring. This can be followed by simple monitoring and, if required, more sophisticated investigations.

4.2.6.4 Penetrometer

The penetrometer is used to determine the integrity of concrete or rock and consists of a specially calibrated spring dynamometer with a pressure-indicating scale on the stem of the handle. It is widely used and well understood.

4.2.6.5 Summary

Many of the techniques used to assess the structural integrity are widely documented and understood. However, these do not cover all the hazards and indicators identified in this scoping study and further research is required to determine which techniques could be adopted and which are not yet used by the reservoir community. A consultation exercise could be undertaken with instrumentation providers to determine suitability for use in embankment dams. This should include retrofitting as well as installation during construction.

The Defra research strategy already includes for a chapter on monitoring and measuring methods for embankment dams in a guide (ranked 9) and publication of a guide to instrumentation and monitoring (ranked 10). Therefore, it is recommended that these projects take into consideration the findings of this scoping study.

Additional projects identified in the Defra strategy should also take into consideration updated information. These projects relate to the inspection and monitoring of tunnels (ranked 13) and guides on embankment dams (ranked 18 and 34).

4.2.7 Other

A number of general techniques were discussed at the workshop and the general consensus was that these could be picked up in an updated guidance document.

4.2.7.1 Simple manual techniques

These include a variety of simple observational methods, such as observation of the turbidity and colour of seepage water, as ways to identify the source of leakage; for example, brown stains that signify the presence of iron may point to groundwater as the source, rather than the reservoir.

Poking an embankment with a rod can also determine, say, areas of weakness, presence of moisture, cavities, etc.

4.2.7.2 Closed-circuit television

Closed-circuit television (CCTV) can be particularly useful where defects below water level are suspected and an inspection is required without lowering the water level, or in areas that are otherwise inaccessible to engineers. Furthermore, CCTV surveys can also be used to carry out inspection of ancillary works, such as pipework and culverts within dams, and so provide information on internal condition and recordable images for future reference and reporting.

4.2.7.3 Endoscope

Like CCTV, endoscopes can be used to carry out internal inspections in locations that are difficult to access for a variety of reasons, such as size, shape, form or location.

An endoscope usually consists of a purpose-made rigid or flexible tube with a light delivery system to illuminate the object under inspection. The light source is normally outside and the light is typically directed via an optical fibre system, with the image transmitted back to the viewer via a system of lenses. Some of the modern endoscopes incorporate a liquid-crystal display (LCD) screen and can display and record both photos and video for future reference and reporting.

The use of endoscopes in dam monitoring is not known and would find application only where conditions dictated.

4.2.7.4 Geophysics techniques (including GPR) and electromagnetic survey

Ground penetrating radar (GPR) is based on the propagation of ultra-high frequency or very high frequency waves through the ground and measuring the time taken for the waves to be reflected back. The waves are reflected by sub-surface cavities or buried objects and the time taken to receive the reflection indicates how deep the object is. GPR is therefore considered more useful for finding suspected targets, rather than for general reconnaissance (Charles *et al.*, 1996). GPR is affected mainly by soil conductivity, which is a function of moisture content, and as a result the method is least effective in saturated clays.

Electromagnetic surveys use two electromagnetic coils to send and receive eddy currents that induce measurable primary and secondary magnetic fields. The method is useful mainly to determine changes in the depth of overburden to detect cavities close to the surface as well as buried concrete objects.

The method gives a good resolution, but is susceptible to interference from metallic objects such as pipes (Charles *et al.*, 1996).

4.2.7.5 Lift-off tests on post-tensioned anchors

Lift-off tests are carried out where post-tensioned tendons or anchors were installed to stabilise a structure such as a concrete dam. The tests are necessary to determine the final force in the anchor after the release of the jacking force and involve jacking the anchor to the load and determining that measurable elongation only occurs after the load. Lift-off tests may be carried out periodically, as in the case of the Hodenpyl Dam in the USA (Bruce *et al.*, 2007); however, they should not be done as a matter of routine, but only when necessary to avoid damage to the grip.

4.2.7.6 Listening sticks on valves

Listening sticks are used to find water leaks and throttled valves, and to check whether valves have been closed; this is done by positioning the stick on the valve or fitting and listening to the sound produced. They are considered to be very effective and can be applied to fittings in dams.

There are manual listening sticks and electronic sticks. The manual listening stick consists of probe bars, a diaphragm and an ear piece and is preferred by some to the electronic listening stick as there is no crackle of electronic noise in the background.

4.2.7.7 Rainfall gauges

Seepage-monitoring systems register rainfall, and could potentially provide erroneous readings. The effect of rainfall on readings should therefore be taken account of and eliminated. The most suitable and cost-effective automatic devices for the measurement of rainfall are the 'tipping bucket' rain gauges (Jacobs, 2007). The gauges are simple and easy to operate and can be linked to a remote monitoring system. They are suitable for both short-term monitoring (events) and long-term monitoring (trends).

4.2.7.8 Reservoir level

Reservoir levels can be measured using a variety of traditional and modern methods, including gauge boards, ultrasonic sensors, pressure transducers and sophisticated telemetric systems.

Although reservoir levels are usually viewed as most important from the reservoir operation point of view, they can be useful in investigating leakage locations and rates, when taken together with rainfall data. Significant changes in reservoir level may also result in embankment deformations (Charles *et al.*, 1996).

4.2.7.9 Seismic measurements

Seismic wave velocity methods are a geophysical method that can be used to carry out dam investigations. The waves can be generated by some form of impact on the surface of the ground or by an explosive charge in the ground. Measurements of seismic wave velocity may indicate the depth of the ground water surface, with the velocity of the direct primary waves and the compression waves refracted from layer interfaces of waves being measured on site and related to fill properties of an embankment.

The method may be unable to detect thin layers and is affected by acoustic noise. Therefore, for shallow sub-surface profiles an alternative method known as seismic reflection is used more commonly (Charles *et al.*, 1996).

4.2.7.10 Vibration monitors

Automated ambient-vibration monitors can be fitted to dams to monitor frequency shifts and the effects of varying water levels. Long-term monitoring would thus provide useful information and advance warning of a problem if unexplained changes in vibration are detected or when the vibrations fall outside the normal envelope.

Vibration monitors may also be installed if there are activities such as construction or excavation taking place in the vicinity of an embankment that are thought to be of some significance with regard to the stability of the structure.

Excessive vibration may also be of concern with regards to the other structures such as draw-off towers.

4.2.7.11 Wind speed and direction

Wind is a factor in the deterioration of concrete in areas where there is a harsh climate. For earth embankments, wind and the associated wave action generated in the reservoir may also cause damage to the upstream surface of the embankment.

Monitoring of wind speeds and direction can be carried out with modern equipment, such as automatic weather stations that incorporate other weather readings (humidity, temperature, pressure, rainfall, etc.) and can log data via telemetry.

4.2.7.12 Remotely operated vehicles

Remotely operated vehicles (ROVs) provide an additional option for inspecting locations that are inaccessible to engineers. There are a variety of ROVs that have various capabilities. Some of the applications within similar spheres include inspection of tunnels and inspection of an ice-covered reservoir.

ROVs send back images in a similar manner to CCTV and endoscopes, which can be studied and stored for future reference.

4.2.7.13 Rapid assessment techniques

Rapid assessment techniques are usually developed for a particular field or area of concern, and aim to provide a way to determine quickly the risk to a structure. Rapid assessment techniques may consist of a series of pre-determined activities. These could include, for example, visual inspection, empirical analyses, stability charts, instrument monitoring data, listening rods, gauges, surveying, etc.

4.2.7.14 Friction on thrust bearings

Friction in thrust bearings at gates can be determined by loading bearings in a test. The test load should match the expected or operational load; if it is greater, this may indicate excessive friction. Also, heating that occurs in the thrust bearings could also signify friction.

4.2.7.15 Monitoring of hydraulic equipment

Monitoring of hydraulic equipment associated with dams may provide early warning of potential problems. For example, excessive vibration can damage valves and pipework, which leads to leakage and eventually possible damage to embankments.

4.2.7.16 Failure of alarm systems

Alarm systems provide a way to alert operators to a fault or failure. However, sometimes the alarm systems themselves fail. An example is the case of Taum Sauk Reservoir in the USA, where pumping in the reservoir continued because of a failure of the water level sensors, which led to overtopping and catastrophic failure (Rodgers and Watkins, 2008). Therefore, additional monitoring methods must be available to provide backup.

4.2.7.17 Summary

A number of general techniques should be picked up in an updated guidance document of monitoring and measuring methods. This should include the above techniques and recommendations on the measurement of reservoir volume.

4.3 Additional methods for concrete and masonry dams

Monitoring techniques for concrete and masonry dams are considered to be covered adequately in CIRIA 148 (Kennard *et al*., 1996).

4.4 Monitoring threats

Threats can also be monitored and provide further information for the risk-assessment process and an ‘early warning’ of a potential hazard developing (and subsequent failure). Common examples are to monitor rainfall or wind, but communication with third parties should also be considered; for example, in an area prone to mine subsidence the Coal Authority may be consulted on historic or current mining activities.

The monitoring of threats is considered to be outside the scope of this report, but some sources of information are provided in Table 4.1. Reservoir levels can be used to analyse incidents caused by some external threats.

Table 4.1 Monitoring and measuring threats.

Threat	Monitoring and measuring techniques
Ageing	Historical data
Aircraft strike	Emergency response
Animal activity	Natural England
Changes in groundwater flow/ chemistry	Environment Agency
Earthquake	BRE Engineering Guide to Seismic Risk to Dams in the UK + www.bgs.ac.uk
Extreme rainfall/ snow/ flood	Weather forecast/ Environment Agency flood warning system
Failure of nearby infrastructure	Emergency response
Failure of reservoir in cascade upstream	Emergency response
Human activity	Undertaker/ Reservoir Manager
Layout, design and construction	Historical data
Mining/ mineral extraction	Arup Review of Mining Instability in Great Britain + www.coal.gov.uk
Operation	Undertaker/ Reservoir Manager
Snow/ ice/ frost	Weather forecast
Sunlight	Undertaker/ Reservoir Manager
Terrorism/ sabotage/ accident	Police
Wind	Weather forecast

4.5 Failure of monitoring techniques

4.5.1 Common problems and constraints

Responses to the questionnaire showed that failures were experienced with some monitoring techniques:

- leakage readings;
- trigger levels/flagging;
- piezometers;
- inclinometers;
- separating seepage from run-off;
- electronic pressure gauges;
- crest monitoring in concrete dams;
- seasonal effects;
- topographic surveys;
- monitoring of slips and slumps;
- settlement cells;
- GPS (although improving with time);
- corrosion and/or deterioration of V-notches and/or gauges (corrosion not inspected);
- plumb-bobs (oil build-up);
- strain gauges (not set up properly and/or difficult to access);
- pendulums breakage;
- untrained monitoring staff.

Key constraints identified with regards to monitoring techniques:

- costs;
- maintenance;
- volume and data;

- consistent recording of data;
- access constraints;
- manpower;
- safety, security and vandalism in public places;
- monitoring flood storage reservoirs – sudden filling;
- lack of fixed monitoring stations.

Workshop delegates commented that clients sometimes don't know what or why they are monitoring and when to take preventative action. Techniques need to be linked to hazards and indicators. It was considered that lessons could be learned from work on flood risk management. Guidance was requested so that engineers and clients would know what to do with monitoring records. A good-practice guide could include examples and differentiate between emergency and routine responses to monitoring results. The guidance note could form part of an asset-management framework and, again, lessons could be learned from work on flood defences.

The design life of instruments is poorly understood, but is very important. Guidance should provide information on the failure of operation as well as on the usefulness of some of the newer techniques.

A guidance document should also cover innovative techniques and it was recommended that geophysical investigation be given a high priority.

A key recommendation derived from the questionnaire responses and workshop discussions was that surveillance is fundamental and can be used to detect problems that would not be picked up by monitoring. It was considered that a guide on surveillance that provided details on the rapid assessment of potential problems would be useful. This should form part of a risk-management process and, ultimately, probability values should be considered for the different hazards identified. Work currently underway on lessons learned from dam incidents should be used to assist with this.

4.5.1.1 Summary

The Defra research strategy already includes for a chapter on monitoring and measuring methods for embankment dams in a guide (ranked 9) and publication of a guide to instrumentation and monitoring (ranked 10). Therefore, it is recommended that these projects take into consideration the findings of this scoping study. Additional projects identified in the Defra strategy should also consider updated information. These projects relate to inspection and monitoring of tunnels (ranked 13) and guides on embankment dams (ranked 18 and 34).

In addition to the projects already identified in the Defra strategy, a guide on surveillance would be considered to be extremely useful by the reservoir community.

4.5.2 Limitations of monitoring the defined indicators

4.5.2.1 Deformations

A number of different mechanisms or processes can cause movements in old embankment dams

- movement caused by slope instability;

- movement caused by internal erosion;
- movements caused by primary consolidation of the fill and foundation, and by collapse compression on inundation;
- volume changes caused by seasonal moisture content;
- deformation of fill caused by changes in reservoir level.

It is important to be able to identify those processes that could seriously impair the dam and possibly lead to serious incidents or failure of the dam.

It is unlikely that monitoring of surface movement will identify slope instability of an existing dam, except in specific circumstances. For instability to occur there must first be a threat or another hazard (see Table A.2). Slope instability by itself has not led to a failure as defined in Section 1.3.

For embankment dams internal erosion is the most common hazard that could lead to failure. Settlement is likely to be localised and therefore routine monitoring at discrete points is unlikely to detect any ongoing erosion. Where an apparent local depression or sinkhole is observed, settlement observation can to determine if settlement is continuing (Robertshaw *et al*. 1998).

The surveying techniques discussed in Section 4.1 are time consuming. For internal displacements, magnet settlement gauges are complex to install. The grout used to backfill the borehole needs to be compatible with the surrounding ground. Their long-term benefit in providing useful information, once a pattern of deformations has been established, is doubtful. Inclinometers can be time consuming to read. Electro-levels require expensive and specialist contractors for the installation. Where wet conditions exist stability problems can occur.

4.5.2.2 Pore-water pressures

Despite their simplicity, a number of problems can occur with standpipe piezometers, which mainly stem from installation:

- A major disadvantage of the standpipe piezometer is that it has to be read manually, although readings are not operator-sensitive provided modern equipment is used with well-charged batteries. The advantage of manual reading is that visual surveillance of the dam can be made.
- A major disadvantage is the length of time it takes to respond to changes in pore-water pressures. However, there are methods to seal transducers into standpipes to obtain a faster response, which can be recorded automatically.
- Failure to seal the sand cell into the borehole can lead to erroneous readings. Formation of a sand cell is relatively straightforward in shallow dry boreholes, but it can be difficult to form a clearly defined sand cell in deep water-filled holes. This can be a particular problem in a clay core, where water is required to stabilise the borehole, and in the upstream fill, where reservoir head is often measured. The formation of slurry at the base of boreholes can block the porous stone and surrounding sand to give erroneous measurements of permeability.
- Failure to prevent water from entering the top of the standpipe can give false readings where the piezometer tip is in low permeability soil. Venting of the standpipe is also required to allow the equilibrium level to be reached. The importance of basic maintenance is vital for long-term operation.
- At many locations protection against vandalism is important.

- Clogging of piezometers can result in misleading results in the long term.

Pneumatic and vibrating wire piezometers need to be de-aired properly for effective operation. Pneumatic piezometers can only be read manually. The readings can sometimes be operator sensitive and the reading can be time consuming. Their long-term reliability is not as good as that of standpipes.

4.5.2.3 Earth pressure in the core

Expertise in the installation and interpretation of earth-pressure cells is limited to a few individuals. The cost of equipment and installation is high. Demonstration of vulnerability to hydraulic fracture as indicated by stress measurements does not necessarily mean that leakage through the core is occurring and that progressive internal erosion is taking place. Except for first filling, no recent incidents of internal erosion through the body of the dam have led to failure. Earth-pressure cells may be of value in the future when the level of a dam is raised such that the top water level increases by a significant amount, or if a more aggressive reservoir operation is required.

Pressuremeters and flat dilatometers have given results with a large scatter, specialist contractors are required for installation and uncased holes are used. These techniques are unlikely to provide reliable data, particularly when gravel is present in the core.

4.5.2.4 Seepage and leakage

Measurements are generally intermittent and can be dominated by rainfall. Nevertheless, they can provide valuable information on leakage rates and the onset of internal erosion. Most of the recent incidents that involved leakage into culverts were detected by visual surveillance. Identification of the source through chemical analysis is not totally reliable and often requires specialists to analyse the data. When using tracers, care is needed in the selection of the tracer because some can pollute reservoir and river water.

The two zonal techniques discussed in Section 4.2.5 have been used at UK reservoirs with some success. Both methods require specialist contractors. The temperature-measurement method is only suitable for dams where it is possible to install the access probes. The method is intrusive and therefore care is required not to damage the structure. In CS-AFDM, as with other geophysical techniques, buried pipes common to many UK embankment dams influence the output. The technique is expensive and is therefore only likely to be used by large dam owners.

4.5.2.5 Structural integrity

Many of the techniques used to assess structural integrity are only useful in the long term, when the development of cracks or displacements become detectable. Some are only used when faults have already developed and may not, therefore, provide the initial indication of a problem. Visual inspection is, once again, a critical part of the assessment of structural integrity.

4.6 Summary – monitoring and measuring techniques

Good descriptions of monitoring and measuring techniques are given in the literature. The questionnaire responses highlighted the possible need for further developments:

- computer modelling, processing, evaluation and presentation of readings;
- zonal techniques (for example, temperature probes);
- reliable dipmeters and seepage monitoring;
- real-time monitoring (for example, telemetry), but one answer stated that this could be a dangerous trend and should not replace site visits;
- triggered alarms;
- remote-sensing techniques (for example, laser sensing, satellites, LiDAR, aerial photos, etc.);
- a comprehensive reference that links hazard and modes of failure to monitoring techniques;
- chemical analysis of drainage flows;
- electro-levels in concrete dams;
- leakage detection;
- methods to measure surface cracking in embankment dams;
- standard inspection guidance to be used by panel engineers.

Several comments were made on the importance of manual readings and site inspections, and the dangers of relying on instrumental and remote readings.

It was also made clear that further information on leakage-detection methods would be useful. It would be valuable to have a trial of ‘zonal detection methods’; temperature methods and CS-AFDMs at a UK dam to compare results, cost and perceived value by the dam owner. An independent assessor would be required.

A summary of the level of understanding within the reservoir community of monitoring and measuring techniques is given in Appendix B.

5 Conclusions

5.1 Current understanding of modes of failure of dams

Knowledge of hazards is required to understand the modes of failure of dams. This scoping study has defined the hazards and a summary of existing and future research requirements for each of the hazards is provided. To understand modes of failure fully, further work is required on risk assessment, but this is outside the scope of this report. The next phase of work should include:

- a review of the likely contribution of any particular hazard to a mode of failure;
- the combining of hazards;
- the probability of occurrence;
- the consequence of failure.

This could be achieved by further exploration of the use of fault trees and event trees.

Requirements for further research and/ or development have been identified throughout the report. These are summarised in Appendix B and incorporated into recommendations in Section 6, where appropriate. In making recommendations, the prioritised list of research projects already identified in the Defra Reservoir Safety Research and Development Strategy has been taken into consideration.

5.2 Summary of available methods to monitor and measure embankment dams

Available methods to monitor and measure embankment dams are generally well documented. The key documents are:

- *Investigating embankment dams: a guide to the identification and repair of defects*. Building Research Establishment Report BR 303 (Charles *et al*. 1996);
- *An engineering guide to the safety of embankment dams in the United Kingdom*, second edition. Building Research Establishment Report BR 363 (Johnston *et al*., 1999).

The conclusion of this scoping study is that the above documents require updating to incorporate some of the less-understood techniques, at least in the reservoir community.

At the time of issue of this report, a key project had just been commissioned by CEATI/DSIG on the development of a 'performance monitoring and data analysis management best-practices report'. It is likely that this will meet much of the above requirement.

In addition to a guide on techniques, an appetite for further guidance on surveillance is apparent. It is recognised widely that monitoring and measuring are useful, but no substitute for inspection by an experienced engineer.

Requirements for further research and/or development are identified throughout the report. These are summarised in Appendix B and incorporated into the recommendations in Section 6, where appropriate. In making recommendations, the prioritised list of research projects already identified in the Defra Reservoir Safety Research and Development Strategy (FCERM, 2009) has been taken into consideration.

5.3 Current understanding of failure of monitoring techniques

The conclusion of the scoping study is that monitoring techniques are not always able to detect failure in advance of an incident. However, many monitoring techniques are implemented without a full understanding of their capabilities and purpose. They could, therefore, be considered as failed techniques because the readings are not understood and they are not related to the monitoring of any particular hazard. Greater understanding of both the purpose of monitoring equipment and its design life is required. Many techniques are used in new construction, but the number used on existing dams is relatively low.

The reservoir community agreed that a guide on the best practice for use of monitoring and measuring techniques would significantly reduce the failure of techniques.

It is likely that the key project commissioned by CEATI/DSIG (see Section 5.3) will go some way to meet the above requirement.

A better understanding is required as to which techniques could be used to understand the potential hazards, with techniques linked to different indicators for each hazard. Further work is needed to identify which techniques could monitor indicators and hazards successfully and therefore be employed as part of a risk-management process.

5.4 Combined results of gap analysis

Results of the gap analysis, carried out through the literature review and discussions at the workshop, are provided in Sections 3 and 4 and general comments received from the questionnaire are summarised in Appendix D. The combined results of the gap analysis indicate a number of areas in which further research or guidance would be useful to the reservoir profession. The work required can be divided into the following categories:

- areas in which existing research can be utilised immediately by the reservoir-safety profession or after some minor development work (**immediate actions**);
- areas that are partly covered within the Defra Reservoir Safety Research and Development Strategy (FCERM, 2009) already, but for which additional information should be taken into consideration when implementing these projects (**augmented or revised R&D projects**);
- areas that require new R&D (**new R&D proposals**);
- areas for which guidance is required, but only after current or planned research (**low-to-medium priority new guidance**) – these are in addition to those topics already covered in the Defra strategy;

These are used as the basis for the recommendations given in Section 6, which also details how these recommendations relate to those in the existing prioritised list of research projects within the Defra Reservoir Safety Research and Development Strategy (FCERM, 2009).

6 Recommendations for future research projects

As a result of this scoping study a number of recommendations for future research projects are made here. They will be implemented only if they fulfil all criteria required for such projects. The recommendations may be modified or combined to fulfil the requirements of the Defra Reservoir Safety Research and Development Strategy (FCERM, 2009) or other related programmes of research. Some of the work proposed in these recommendations may be incorporated into existing studies. It is not possible to confirm at this time which, if any, of these recommendations will be taken forward.

6.1 Immediate actions

6.1.1 Reservoir Technical Guidance Note: surface erosion

Research undertaken as part of the FLOODsite project should be reviewed and information relevant to reservoirs extracted to form a Technical Guidance Note for publication and circulation to reservoir professionals. If appropriate, this can simply include links to the relevant information within FLOODsite. Reference should be made to comments in Sections 3.1.22 and 3.1.23 of this report.

Further research or guidance may follow in the future (see Section 6.4).

6.1.2 Reservoir Technical Guidance Note: upstream membranes, and concrete and asphaltic concrete facing

Research undertaken as part of the FLOODsite project (Tasks 2 and 4) should be reviewed and information relevant to reservoirs extracted to form a Technical Guidance Note for publication and circulation to reservoir professionals. If appropriate, this can simply include links to the relevant information within FLOODsite. Reference should be made to comments in Sections 3.1.26, 3.1.29, 3.1.30 and 3.1.41 of this report. Further work on upstream membranes may follow work on wave protection and climate change (see Section 6.2).

6.1.3 Reservoir Technical Guidance Note: crest fissuring

Research undertaken through FRMRC should be reviewed and information relevant to reservoirs extracted to form a Technical Guidance Note for publication and circulation to reservoir professionals. If appropriate, this can simply include links to the relevant information already published. Reference should be made to comments in Section 3.1.45 of this report.

6.1.4 Reservoir Technical Guidance Note: controlled holding of water at a low level

Research undertaken through FRMRC should be reviewed and information relevant to reservoirs extracted to form a Technical Guidance Note for publication and circulation to reservoir professionals. If appropriate, this can simply include links to the relevant information already published. Reference should be made to comments in Section 3.1.46 of this report.

6.2 Augmented or revised research and development projects

The scoping study identified a number of areas that currently lack research or guidance, but for which related research or development has already been identified in the Defra Reservoir Safety Research and Development Strategy (FCERM, 2009). For these areas, notes are provided in the table in Appendix C, which is based on the prioritise list included within the strategy. It is recommended that notes in the table are considered when the full specification for these projects is prepared in accordance with the programme.

6.3 New research and development proposals

Six potential new R&D projects are proposed are in addition to those already included in the priority list in Defra's strategy (Appendix C). Partially completed 'proposal for future research projects' forms are included in Appendix E, to assist with the specification for these elements of work.

Recommended projects of *high priority* are:

- Reservoirs and Ecological Hazards: A Best-Practice Guide to the Management of Animals and Vegetation;
- Reservoir Safety: A Checklist for Surveillance;
- Modes of Failure of Dams – Trial Risk Assessment.

Recommended projects of *medium-to-high priority* are:

- Monitoring Techniques for Different Indicators;
- Risk Management of Reservoirs – A Best-Practice Guide;
- Reservoir Engineering Design to Eurocodes: Draft Guide for Consultation.

Full details of the recommended proposals are included in Appendix E, along with recommended timescales for completion. The 'Modes of Failure of Dams – Trial Risk Assessment' proposal should be included in the 'Guide to Risk Assessment' project, which is expected to commence imminently.

6.4 Low-to-medium priority new research and guidance

Much currently on-going research relates to modes of failure of dams and techniques to monitor and measure these. When the various research projects are concluded, it will be beneficial to produce further guidance based on the findings. Currently, guidance notes for these hazards are considered to be of medium priority, both because the significance of the hazards will not be fully understood until research has been advanced and because they are not identified on the priority list in Defra's research strategy.

The areas that require new guidance documents in future, after completion of current research, are:

- high uplift pressures (Sections 3.1.17 and 3.1.18);
- deterioration of upstream membrane, concrete and/or asphalt (Sections 3.1.29, 0 and 3.1.41);
- damage to ancillary structures (Section 3.1.34);
- controls, valves and/or gates (Section 3.1.35);
- surface erosion (Sections 3.1.13–3.1.15, 3.1.22, 3.1.37 and 3.1.41);
- monitoring of earth pressure in core (Section 4.2.4);
- comparison of total-station and laser-scanning techniques to monitor movements in earth embankments, using Chestnut North Reservoir as a case study (Section 4.2.2).

This guidance may take the form of Technical Guidance Notes. These projects may become a higher priority after the current and proposed research (see Sections 3 and 4 for further detail).

In addition to the above, a number of areas would benefit from new research. These are considered to be of medium priority at this stage but, again, such projects may become higher priority after the current and proposed research. The areas that may benefit from future new research are:

- deterioration of cores in embankment dams (Section 3.1.24);
- chemical attack on fill or rockfill in dams (Section 3.1.31).

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Appendix A

Framework for Scoping Study

Table A.1 Defined hazards.

Report section:	Hazard: / Threat:	Aging	Aircraft strike	Animal activity	Changes in groundwater flow/ chemistry	Earthquake	Extreme rainfall/ snow/ flood	Failure of nearby infrastructure	Failure of reservoir in cascade upstream	Human activity	Ice/ frost	Layout, design or construction inadequate or inappropriat	Mal-operation	Mining/ mineral extraction	Sunlight	Terrorism/ sabotage/ accident	Water loading	Wind
3.1.1	Differential settlement or deformation	x	x					x						x				
3.1.2	Rapid drawdown												x				x	
3.1.3	Reduced freeboard	x				x				x		x	x					
3.1.4	Settlement (consolidation) of embankment			x													x	
3.1.5	Settlement of foundation	x	x											x				
3.1.6	Seepage	x		x						x							x	
3.1.7	Concentrated erosion	x										x					x	
3.1.8	Backward erosion (piping)	x										x						
3.1.9	Contact erosion	x										x					x	
3.1.10	Internal erosion adjacent to appurtenant structure	x										x					x	
3.1.11	Suffosion	x										x					x	
3.1.12	Problematic embankment fill materials (e.g. peat)											x						
3.1.13	Animal activity	x		x														
3.1.14	Vegetation	x								x								
3.1.15	Features on the downstream face									x		x	x			x		
3.1.16	High pore water pressures											x	x				x	
3.1.17	High uplift pressures on foundation				x												x	
3.1.18	High uplift pressures on lift joints				x												x	
3.1.19	Hydraulic fracture											x					x	
3.1.20	Blockage of spillway							x		x			x			x		
3.1.21	Inadequate energy dissipation						x					x						
3.1.22	Out-of-channel flow in spillway						x					x					x	
3.1.23	Overflow capacity exceeded						x	x	x	x	x	x	x				x	
3.1.24	Deterioration of core																	
3.1.25	Concrete cut-off deterioration	x			x													
3.1.26	Concrete deterioration by chemical or other attack	x																
3.1.27	Deterioration in foundation soil strength	x			x													
3.1.28	Deterioration of concrete or rock foundation	x			x													
3.1.29	Deterioration of upstream membrane									x						x		x
3.1.30	Deterioration of concrete facing or asphaltic concrete									x						x		x
3.1.31	Chemical attack on fill or rockfill							x										
3.1.32	Blocked drains/ relief well	x						x		x			x					
3.1.33	Blocked screens	x						x										
3.1.34	Other damage to ancillary structures	x									x							
3.1.35	Failure of controls/ valves/ gates									x			x					
3.1.36	Hydrodynamic forces resulting in structural damage/ failure						x					x					x	
3.1.37	Local runoff on mitre resulting in erosion						x											
3.1.38	Surge in pipework									x		x	x			x	x	
3.1.39	Corrosion	x													x			
3.1.40	Failure of bywash channels	x										x		x				
3.1.41	Wave attack on upstream face						x										x	x
3.1.42	Wave carry-over / wave slop (wave overtopping)						x					x					x	
3.1.43	External threat causing wave or damage					x		x	x									
3.1.44	Wave wall inadequacy											x						
3.1.45	Crest fissuring or rutting									x								
3.1.46	Controlled holding of water at a lower level												x				x	
3.1.47	Exceeding intended design loads in use of dam or ancillary structures							x					x				x	
3.1.48	Earthquake loading					x												

Table A.2 Defined modes of failure.

Report section:	Hazard:	Catastrophic overtopping (3.2.1)	Dam breach (3.2.2)	Foundation failure of concrete dam (3.2.3)	Foundation failure of embankment dam (3.2.4)	Instability of concrete dam (3.2.5)	Instability of embankment dam (3.2.6)	Overflow failure (3.2.7)	Structural failure of concrete dam (3.2.8)	Structural failure of embankment dam (deterioration of core) (3.2.9)	Structural failure of embankment dam (load exceeded) (3.2.10)	Uncontrolled flow due to appurtenant works failure (3.2.11)
3.1.1	Differential settlement or deformation			x		x	x	x				
3.1.2	Rapid drawdown					x	x					
3.1.3	Reduced freeboard	x	x					x				
3.1.4	Settlement (consolidation) of embankment							x				
3.1.5	Settlement of foundation						x	x	x			
3.1.6	Seepage		x									
3.1.7	Concentrated erosion											
3.1.8	Backward erosion (piping)											
3.1.9	Contact erosion											x
3.1.10	Internal erosion adjacent to appurtenant structure		x									
3.1.11	Suffosion		x									
3.1.12	Problematic embankment fill materials (e.g. peat)		x		x		x					
3.1.13	Animal activity		x				x					
3.1.14	Vegetation		x									
3.1.15	Features on the downstream face		x				x					
3.1.16	High pore water pressures		x			x						
3.1.17	High uplift pressures on foundation		x	x		x	x					
3.1.18	High uplift pressures on lift joints		x			x						
3.1.19	Hydraulic fracture		x									
3.1.20	Blockage of spillway		x					x				
3.1.21	Inadequate energy dissipation		x					x				
3.1.22	Out-of-channel flow in spillway		x					x				
3.1.23	Overflow capacity exceeded		x					x				
3.1.24	Deterioration of core		x									
3.1.25	Concrete cut-off deterioration								x	x		
3.1.26	Concrete deterioration by chemical or other attack			x				x	x			
3.1.27	Deterioration in foundation soil strength				x		x					
3.1.28	Deterioration of concrete or rock foundation			x		x	x		x			
3.1.29	Deterioration of upstream membrane		x									
3.1.30	Deterioration of concrete facing or asphaltic concrete		x									
3.1.31	Chemical attack on fill or rockfill		x				x					
3.1.32	Blocked drains/ relief well			x		x	x		x			
3.1.33	Blocked screens							x				
3.1.34	Other damage to ancillary structures							x	x			
3.1.35	Failure of controls/ valves/ gates		x					x				x
3.1.36	Hydrodynamic forces resulting in structural damage/ failure							x				
3.1.37	Local runoff on mitre resulting in erosion		x									
3.1.38	Surge in pipework		x								x	
3.1.39	Corrosion											x
3.1.40	Failure of bywash channels	x										
3.1.41	Wave attack on upstream face		x									
3.1.42	Wave carry-over / wave slop (wave overtopping)		x					x				
3.1.43	External threat causing wave or damage	x	x					x				
3.1.44	Wave wall inadequacy		x					x				
3.1.45	Crest fissuring or rutting		x									
3.1.46	Controlled holding of water at a lower level		x									
3.1.47	Exceeding intended design loads in use of dam or ancillary structures		x	x	x	x	x					x
3.1.48	Earthquake loading	x	x			x	x	x			x	x

Table A.3 Framework of indicators.

	Location:	Crest		Upstream shoulder				U/S of core	Central core						Downstream shoulder							Into culvert/shaft				Downstream				Foundation	Abutments	Reservoir rim	General
	Indicator:	Settlement	Horizontal displacement	Settlement	Horizontal displacement	Pore pressure	Permeability	Settlement	Settlement	Horizontal displacement	Stress in core/ hydraulic fracture	Pore pressure	Permeability	Leakage location	Pore pressure	Permeability	Leakage location	Leakage rate	Settlement	Horizontal displacement	Turbidity	Leakage location	Leakage rate	Turbidity	Structure distress	Settlement	Horizontal displacement	Pore pressure	Permeability				
Report section:	Hazard:																																
3.1.1	Differential settlement or deformation																																
3.1.2	Rapid drawdown																																
3.1.3	Reduced freeboard																																
3.1.4	Settlement (consolidation) of embankment																																
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3.1.13	Animal activity																																
3.1.14	Vegetation																																
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3.1.16	High pore water pressures																																
3.1.17	High uplift pressures on foundation																																
3.1.18	High uplift pressures on lift joints																																
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3.1.29	Deterioration of upstream membrane																																
3.1.30	Deterioration of concrete facing or asphaltic concrete																																
3.1.31	Chemical attack on fill or rockfill																																
3.1.32	Blocked drains/ relief well																																
3.1.33	Blocked screens																																
3.1.34	Other damage to ancillary structures																																
3.1.35	Failure of controls/ valves/ gates																																
3.1.36	Hydrodynamic forces resulting in structural damage/ failure																																
3.1.37	Local runoff on mitre resulting in erosion																																
3.1.38	Surge in pipework																																
3.1.39	Corrosion																																
3.1.40	Failure of bywash channels																																
3.1.41	Wave attack on upstream face																																
3.1.42	Wave carry-over / wave slop (wave overtopping)																																
3.1.43	External threat causing wave or damage																																
3.1.44	Wave wall inadequacy																																
3.1.45	Crest fissuring or rutting																																
3.1.46	Controlled holding of water at a lower level																																
3.1.47	Exceeding intended design loads in use of dam or ancillary structures																																
3.1.48	Earthquake loading																																

Table A.4 Techniques to monitor and measure different indicators.

Location	Indicator: / Technique:	Deformations								Pore water pressures			Earth pressure in core			Seepage and leakage											Structural integrity				Other									
		Surface				Internal										General								Zonal																
		Crest levelling	Precise surveying - whole embankment	Remote sensing - satellite, LIDAR & aerial photos	Sighting rods	Electro-levels	Inclinometers	Magnet settlement gauges	Slip indicators	Hydraulic piezometers	Pneumatic and vibrating wire piezometers	Standpipe piezometers	Critical pressure	Pressuremeter and dilatometer	Push-in spade cells	Bucket of water	Chamber with sump/settlement tank	Divining rods	Jug & stopwatch	Observation wells	Tracers/chemical analysis	Under drain flows	V-notch weirs	CSFDM	Resistivity	Temperature	Crack meters / tell-tales	Hammer tap	Pendulum in valve tower	Probing/ penetrometer	CCTV	Endoscope	Geophysics (incl. Ground Penetrating Radar, electromagnetic survey	Lift off tests on post-tensioned anchors	Listening sticks on valves	Rainfall gauges	Reservoir level	Seismic measurements	Vibration monitors (if construction/ excavation nearby)	Wind speed/direction
Crest	Settlement	1	1					2																																
	Horizontal displacement		1			3	2																																	
Upstream shoulder	Settlement	1	1																																					
	Horizontal displacement		1		1																																			
	Pore pressure										1	1																					3							
	Permeability											1																					2							
U/S of core	Settlement	1	1					2																																
Central core	Settlement	1	1	2				3																																
	Horizontal displacement					3	3																						1											
	Stress in core/ hydraulic fracture												1	3	1																									
	Pore pressure									3	2	1																												
	Permeability											1																												
	Leakage location											2																					2							
Downstream shoulder	Pore pressure									3	3	1																					3							
	Permeability											1																					2							
	Leakage location																1		1		2		1	2	3	2							2			1	1			
	Leakage rate															1	1	3	1				1																	
	Settlement																																							
	Horizontal displacement		2		2																																			
	Turbidity																1		1																	1				
Into culvert/shaft	Leakage location																1		1		2		1	2	2	2							2							
	Leakage rate																1		1				1													1	1			
	Turbidity																1		1																					
	Structure distress																										1		2											
Downstream	Settlement	1																																						
	Horizontal displacement	1																																						
	Pore pressure											1																					3							
	Permeability											1																												
Foundation																																								
Abutments				2								2																												
Reservoir rim				3			3					1																												2
General																				1								1		1			2	1	1		1		3	

1 = useful often used

2 = could be useful, but used rarely

3 = used very occasionally

Appendix B

Summary of findings

	Hazard:	Level of understanding in reservoir community/ further research required:
3.1.1	Differential settlement or deformation	Consider re-issuing existing guidance.
3.1.2	Rapid drawdown	Further guidance required, but low priority.
3.1.3	Reduced freeboard	Further guidance required on related hazards, see below, but none on freeboard itself.
3.1.4	Settlement (consolidation) of embankment	No further research required. However, it is noted that research is being undertaken on unsaturated soils.
3.1.5	Settlement of foundation	No further research required.
3.1.6	Seepage	Requires further research but this is likely to be covered by research on internal erosion, which is currently underway. Ultimately guides may need to be updated. See also Section 4.6 (monitoring and measuring techniques).
3.1.7	Concentrated erosion	Requires further research but this is likely to be covered by research on internal erosion, which is currently underway. Ultimately guides may need to be updated.
3.1.8	Backward erosion (piping)	Requires further research but this is likely to be covered by research on internal erosion, which is currently underway. Ultimately guides may need to be updated.
3.1.9	Contact erosion	Requires further research but this is likely to be covered by research on internal erosion, which is currently underway. Ultimately guides may need to be updated.
3.1.10	Internal erosion along an appurtenant structure	Requires further research but this is likely to be covered by research on internal erosion, which is currently underway. Ultimately guides may need to be updated.
3.1.11	Suffosion	Requires further research but this is likely to be covered by research on internal erosion, which is currently underway. Ultimately guides may need to be updated.
3.1.12	Problematic embankment fill materials (for example peat)	Consider for further research, although this is often very site specific. As a minimum consider for inclusion in any future/ revised guidance note.
3.1.13	Animal activity	Further guidance required. Consult with ecological community; conflicting legislation must be considered. Take into account findings of recent international research. This is a high priority.
3.1.14	Vegetation	Further guidance required. Consult with ecological community; conflicting legislation must be considered. Take into account findings of recent international research. This is a high priority.
3.1.15	Features on the downstream face	Further guidance required on surface erosion incorporating findings of international research. Practical checklist for inspections recommended.
3.1.16	High pore-water pressures	No further research required. However, guidance on correct interpretation of monitoring required (see Section 4.6).
3.1.17	High uplift pressures on foundation	Further guidance on high uplift pressures on embankment dams is required but international research is underway. Guidance should consider findings of existing research on flood defence structures. Review or try and influence research to consider use of non-linear numerical analysis techniques.
3.1.18	High uplift pressures on lift joints	No further research required. Review research on non-numerical linear analysis techniques when undertaken; this has been recommended in the Defra strategy.
3.1.19	Hydraulic fracture	Research required on the link between hydraulic fracture and internal erosion. This should be covered by the research on internal erosion, which is currently underway. Ultimately guides may need to be updated.
3.1.20	Blockage of spillway	It is recommended that the research on spillways, identified in the Defra strategy, is broadened to include spillways and overflow works in general (not just masonry). No specific research on blockage required.
3.1.21	Inadequate energy dissipation	Further guidance required. It is recommended that the research on spillways, identified in the Defra strategy, is broadened to include spillways and overflow works in general and that this includes production of a design, construction, inspection and maintenance guide.

	Hazard:	Level of understanding in reservoir community/ further research required:
3.1.22	Out-of-channel flow in sillway	Research from FLOODSite can be used to provide information on surface erosion. It is recommended that the research on spillways, identified in the Defra strategy, is broadened to include spillways and overflow works in general.
3.1.23	Overflow capacity exceeded	Research from FLOODSite on flood embankments can be used for information on surface erosion. Further research is required on the hazard of spillway and overflow capacity being exceeded.
3.1.24	Deterioration of core	Further research required. Consider incorporating some of this into wider research on concrete deterioration. Include hazard in updates of key documents.
3.1.25	Concrete cut-off deterioration	Further guidance required. It is recommended that the research on concrete cut-offs and grout curtains, identified in the Defra strategy, is broadened to include concrete deterioration.
3.1.26	Concrete deterioration by chemical or other attack	A manual should be produced as has been recommended in the Defra strategy. Reference should be made to Eurocode 2.
3.1.27	Deterioration in foundation soil strength	Further guidance required. Consider incorporating in research on internal erosion, which is currently underway.
3.1.28	Deterioration of concrete or rock foundation	Update of existing guidance required. Consider incorporating this in projects coming out of Defra's strategy involving degradation and repair of concrete dams. Reference should be made to Eurocode 2.
3.1.29	Deterioration of upstream membrane	Update of existing guidance required. This should incorporate findings from FLOODSite Task 4. Review research on wave protection and the direct and indirect impacts of climate change when undertaken; this has been recommended in the Defra strategy.
3.1.30	Deterioration of concrete facing or asphaltic concrete	Update of existing guidance required. This should incorporate findings from FLOODSite Task 2. Review research on wave protection and the direct and indirect impacts of climate change when undertaken; this has been recommended in the Defra strategy. Research on the implications of Eurocode 2 is also recommended.
3.1.31	Chemical attack on fill or rockfill	Research required. This could be incorporated in the research on climate change, identified in the Defra strategy. However, it may need to be a separate project.
3.1.32	Blocked drains and relief wells	No further research required.
3.1.33	Blocked screens	No further research required, but proposed in Defra strategy.
3.1.34	Other damage to ancillary structures	Update of existing guidance required, however, this has already been identified in the Defra strategy.
3.1.35	Failure of controls, valves or gates	Update of existing guidance required following research already identified in the Defra strategy. Research on the implications of Eurocode 3 is also recommended. Data gathering from old reservoirs under 25,000 m^3 is recommended.
3.1.36	Hydrodynamic forces that result in structural damage or failure	Further guidance required. It is recommended that the research on spillways, identified in the Defra strategy, is broadened to include spillways and overflow works in general.
3.1.37	Local run-off on mitre that results in erosion	Further guidance on erosion is required, but international research is underway. Review research on the direct and indirect impacts of climate change when undertaken; this has been recommended in the Defra strategy. Consider guide on surveillance.
3.1.38	Surge in pipework	Update of existing guidance required, however, this has already been identified in the Defra strategy. Research on the implications of Eurocode 3 is also recommended.
3.1.39	Corrosion	Update of existing guidance required, however, this has already been identified in the Defra strategy. Reference should be made to Eurocode 3.
3.1.40	Failure of bywash channels	Further research required. This could be incorporated into projects coming out of the Defra strategy relating to overflow works. Consider hazard in updates to key documents.
3.1.41	Wave attack on upstream face	Update of existing guidance required; however, this has already been identified in the Defra strategy.

	Hazard:	Level of understanding in reservoir community/ further research required:
3.1.42	Wave carry-over and wave slop (wave overtopping)	Update of existing guidance required, based on recent international published research. Further research required regarding the effect of wind speed on overtopping enhancement by spray. This could be incorporated into projects coming out of the Defra strategy relating to waves.
3.1.43	Wave caused by external threat	No further research required.
3.1.44	Wave-wall inadequacy	Further research required, however this has already been identified in the Defra strategy.
3.1.45	Crest fissuring or rutting	Update of existing guidance using research undertaken within the FRMRC. Consider guide on surveillance.
3.1.46	Controlled holding of water at a lower level	Update of existing guidance taking into consideration research undertaken within the FRMRC on fissuring. Consider guide on surveillance.
3.1.47	Exceeding intended design loads in use of dam or ancillary structures	Guidance required on relationship between dam owners, engineers and public.
3.1.48	Earthquake loading	No further research required. However, research on the implications of Eurocode 7 and Eurocode 8 is recommended and guides may ultimately need updating.

Monitoring and measuring techniques:	Level of understanding in reservoir community/ further research required:
Commonly used methods	Common methods are taken to be well understood and used. Considerable guidance is given in BRE report 303 (1999) which is the key reference for monitoring and measuring techniques. BRE 303 is likely to require updating to include new research and methods.
Deformations	Common techniques include physical and remote surveys, including new methods such as LiDAR. It is recognised that these techniques are used more frequently on flood embankments and some lessons could be learned on reservoirs. Geophysical techniques could be useful, but are poorly understood. Guidance should be updated to take account of new methods. In particular Ground Penetrating Radar and electromagnetic surveys deserve further attention.
Pore water pressures	Piezometers are widely used, in particular the standpipe type. There was a lack of understanding of what to do with data and why it is collected. Updated guidance is required, focusing on cost information, reliability and effectiveness of the different instruments. Information available within the geotechnical community should be used as the basis for guidance.
Earth pressure in core	Measurement of earth pressure is non-routine and rarely used. Techniques are often used in construction, rather than monitoring existing structures. However, given the on-going research on internal erosion, this is an area that is likely to require greater understanding in the future.
Seepage and leakage	It is recommended that more monitoring techniques should be focused on this aspect as detection of leaks is complex and difficult. There is a variety of methods available, ranging from simple to complex/hi-tech. The simplest techniques are used most frequently. New techniques such as Controlled Source Frequency Domain Magnetics (CSFDM) and geophysics require further guidance, possibly in the form of case studies, and potentially further research in future. Understanding of seepage issues is likely to become more
Structural integrity	Surveillance and the use of basic techniques for assessing structural integrity are highlighted. The techniques are considered useful, but do not cover all the indicators and hazards identified in this scoping study. Further research is required and this could include consultation with instrumentation providers.
Other	A number of general techniques were discussed at the workshop which recommended that an updated guidance document is required to incorporate techniques such as CCTV, endoscopes, vibration monitors, etc.

Appendix C

Comments on prioritised list of research projects in Defra Reservoir Safety Research and Development Strategy

Rank	Projects Descriptions	Output	Recommended augmentations or revisions based on findings of scoping study (refer to sections of scoping study report indicated for full details)	R&D projects and new guidance proposed in scoping study, which should be programmed in line with these projects (refer to appropriate recommendation section of scoping study report)
1	Review latest knowledge on internal erosion leading to updated UK guidance	Scoping review >> revised guide	A guide is definitely required and should take into consideration on-going research (including that high-lighted in 3.1.6 to 3.1.11 and 3.1.19). Consider incorporating research into 'deterioration in foundation soil strength' (3.1.27).	
2	Review of Modes of Failure of Dams and Failure of Monitoring Techniques	Report and Guide	A guide is definitely required and should build on the work in the scoping study. This should include clear, definitive descriptions of the different failure modes, including processes, links to indicators (that in turn reflect upon visual inspection and monitoring equipment), diagrams and photos.	New guide 'Reservoir Safety: A Checklist for Surveillance' (6.3). New R&D Project 'Modes of Failure of Dams – Trial Risk Assessment' (6.3).
3	Research and guidance on the behaviour of masonry spillways	Science: Guidance	It is recommended that the research on spillways is broadened to include spillways and overflow works in general (not just masonry). The guide should include design, construction, inspection and maintenance (3.1.20 to 3.1.23 and 3.1.36). Also include information on 'failure of bywash channels' (3.1.40) Consider linking spillway projects (21 and 42 below).	
4	Publication - Lessons from Dam Incidents	Report		
5	Collect geotechnical and geological data of old dams for EA Database	Research/ Database	Obtain data on type of instrumentation used in the dams.	
6	Review of direct impacts of climate change on dams and reservoirs	Report	Recommend that this is augmented to include 'deterioration of upstream membrane' (3.1.29); 'deterioration of concrete facing or asphaltic concrete' (3.1.30); 'local runoff on mitre resulting in erosion' (3.1.37) and 'landslide into reservoir' (3.1.49). Consider 'chemical attack on fill or rockfill' (3.1.31).	
7	Review of existing methods and development of guidelines for dambreak assessment	Science and Guidance		
8	Extreme flood hydrology 1) Finalise the improved methods for extreme rainfall event predictions; 2) Develop a tool for implementing the new method; 3) Develop a rainfall-runoff method appropriate for modelling extreme floods	New Method: Tool		
9	Monitoring and measuring methods for embankment dams	Chapter in Guide	Ensure this includes updated information on techniques (4.2.2 to 4.2.7). In addition, guidance should differentiate between routine and emergency responses to monitoring results (4.5.1).	New guide 'Reservoir Safety: A Checklist for Surveillance' (6.3). New R&D Project 'Monitoring Techniques for Different Indicators' (6.3).
10	Publication - A Guide to Instrumentation and Monitoring	Report and Guide	Ensure this includes information on 'high pore water pressures' (3.1.16). Ensure this includes updated information on techniques (4.2.2 to 4.2.7). In addition, guidance should differentiate between routine and emergency responses to monitoring results (4.5.1) and should be related to the design expectations for the dam.	New guide 'Reservoir Safety: A Checklist for Surveillance' (6.3). New R&D Project 'Monitoring Techniques for Different Indicators' (6.3).
11	Training in dambreak analysis and evaluation	Training		
12	Training for event management	Research; Guidance		
13	Guide on inspection, monitoring, maintenance and repair of tunnels	Guide	Ensure this includes updated information on techniques (4.2.2 to 4.2.7) as appropriate.	New R&D Project 'Monitoring Techniques for Different Indicators' (6.3).

Rank	Projects Descriptions	Output	Recommended augmentations or revisions based on findings of scoping study (refer to sections of scoping study report indicated for full details)	R&D projects and new guidance proposed in scoping study, which should be programmed in line with these projects (refer to appropriate recommendation section of scoping study report)
14	Compendium of design and assessment of embankment dams- collaboration of work	Research		
15	Revise CIRIA guide 'Design of Flood Storage Reservoirs - B14'	Guidance		
16	Methods of raising embankment dams	Guide		
17	Dambreak analysis - Structure failure mechanisms	Scope; Science; Guidance		
18	Update the guide of Small Embankment Dams	Updated guide	See 34 below 'Guide to safety of embankment dams'. Some of this will be relevant to this guide, but is likely to be required in less detail.	
19	Update the 'Floods and Reservoir Safety: An Engineering Guide manual	Update		
20	Retrofitting of filters to cope with internal erosion	Review		
21	Review Alternative Materials & Techniques for Embankment Dam Auxiliary Spillways	Report/ Guide		
22	A Guide to Mechanical and Electrical Equipment in Dams	Guide	Include guidance on 'control of pipes/ valves/ gates' (3.1.35)	
23	Development of UK-based Risk Assessment Methodology - PRA	Guide	This should seek to clarify definitions and risk assessment model to be adopted, providing a consistent approach for future work.	New R&D Project 'Modes of Failure of Dams – Trial Risk Assessment' (6.3).
24	Research to identify failure modes and processes	Report or Guide	This should seek to clarify definitions, providing a consistent approach for future work.	New guide 'Reservoir Safety: A Checklist for Surveillance' (6.3). New R&D Project 'Modes of Failure of Dams – Trial Risk Assessment' (6.3).
25	Manual on the degradation and repair of concrete dams	Report	Include 'concrete deterioration by chemical or other attack' (3.1.26) and 'deterioration of concrete or rock foundation' (3.1.28). Consider augmenting this to include concrete cores.	Low to medium priority research in future on 'deterioration of cores in embankment dams' (6.4).
26	Review and Update of CIRIA Guide to Valves, Pipe work and Associated Equipment	Guide	Include guidance on 'surge in pipework' (3.1.38) and 'corrosion' (3.1.39).	
27	Review and Update of 1996 Engineering Guide to the Safety of Concrete and Masonry Dams	Guide	Include guidance on uplift pressures, which should come out of 41 below (therefore consider linking projects). Include 'concrete cut-off deterioration' (3.1.25); 'concrete deterioration by chemical or other attack' (3.1.26); 'deterioration of concrete or rock foundation' (3.1.28);'failure of controls/ valves/ gates' (3.1.35) 'corrosion' (3.1.39); 'failure of bywash channels' (3.1.40). Ensure this includes updated information on techniques (4.2.2 to 4.2.7) as appropriate for concrete dams. In addition, guidance should differentiate between routine and emergency responses to monitoring results (4.5.1).	New guide 'Reservoir Safety: A Checklist for Surveillance' (6.3). Low to Medium Priority guidance note on 'high uplift pressures on foundation' (6.4).
28	Embankment and Grout Curtains & Cutoffs	Research	Include 'concrete cut-off deterioration' (3.1.25).	
29	Review science and practice supporting emergency planning for dams (including UK, EC and US projects)	Scoping review >> R&D needs & best practice		
30	Slip Lining of Conduits	Research		
31	Decommissioning of dams	Guide		

Rank	Projects Descriptions	Output	Recommended augmentations or revisions based on findings of scoping study (refer to sections of scoping study report indicated for full details)	R&D projects and new guidance proposed in scoping study, which should be programmed in line with these projects (refer to appropriate recommendation section of scoping study report)
32	Review methods for predicting return period of events > 10,000 years to support risk-based assessments	Scoping review >> revised guide		
33	Understanding and reducing uncertainty within dambreak analyses	Research, Guidance		
34	Guide to safety of embankment dams	Updated Guide	Include information on: 'differential settlement/ deformation' (3.1.1); 'rapid drawdown' (acceptable rates of)(3.1.2); 'problematic embankment fill materials (e.g. peat) (3.1.12); 'animal activity' (3.1.13); 'vegetation (3.1.14); 'feautures on downstream face' (3.1.15); 'high uplift pressures on foundation' (3.1.17); 'failure of controls/ valves/ gates' (3.1.35) 'corrosion' (3.1.39); 'failure of bywash channels' (3.1.40); 'crest fissuring/ rutting' (3.1.45); 'controlled holding of water at a lower level' (3.1.46). Photographs and diagrams should be included. Ensure this includes updated information on monitoring and measuring techniques (4.2.2 to 4.2.7). In addition, guidance should differentiate between routine and emergency responses to monitoring results (4.5.1).	New guide 'Reservoirs and Ecological Hazards: A Best Practice Guide to the Management of Animals and Vegetation' (6.3). New guide 'Reservoir Safety: A Checklist for Surveillance' (6.3).
35	Guidance on public safety at dams	Guide	See 39 below 'Management Communication Strategy'.	
36	Dambreak analysis - Data and forensics	Data		
37	Review & Guidance on Techniques for Installation and Operation of Draw off System	Report/ Guide		
38	Waves on reservoirs - 1) Wave height prediction in shallow water where interference of wave trains occurs; 2) wave impact forces on wave walls - in particular 'dry stone' walls and adequacy of wave walls to withstand waves and; 3) Guidance on wave wall protection	Science: Guidance	Recommend that this is augmented to include 'deterioration of upstream membrane' (3.1.29) and 'deterioration of concrete facing or asphaltic concrete' (3.1.30). Also consider including assessment of the effect of wind speed on overtopping enhancement by spray.	
39	Management Communication Strategy	Strategy	Incorporate guidance on 'exceeding intended design loads in use of dam or ancillary structures' (3.1.47).	
40	Development of a web-based GIS management system for dams	Tool		
41	Non-linear numerical analysis of concrete dams and their foundations	Report		
42	Review tools to reduce O&M costs for extended life of spillways	Report		
43	Review of indirect impacts of climate change on dams and reservoirs	Report	See 6 above 'Review of direct impacts of climate change on dams and reservoirs'.	Low to Medium Priority research relating to 'chemical attack on fill or rockfill' (6.4.).
44	Application of Reservoir flood forecasting and control to UK reservoirs	Guidance		
45	Procedures for the Assessment of Intake Towers and Gates	Report		
46	Review management methods, inspection and standards and inspection intervals and develop new requirements to take account of climate change	Guidance		

Rank	Projects Descriptions	Output	Recommended augmentations or revisions based on findings of scoping study (refer to sections of scoping study report indicated for full details)	R&D projects and new guidance proposed in scoping study, which should be programmed in line with these projects (refer to appropriate recommendation section of scoping study report)
47	Investigate methods and technologies to help dams adapt to climate change	Guidance	Recommend that this is augmented to include 'deterioration of upstream membrane' (3.1.29); 'deterioration of concrete facing or asphaltic concrete' (3.1.30) and 'local runoff on mitre resulting in erosion' (3.1.37).	
48	Knowledge optimisation on data (after B, E)	Tools		
49	Guidance on the location, design and maintenance of fish screens	Guide		

Appendix D

Comments received on responses to questionnaire

Results of the gap analysis, carried out through the literature review and discussions at the workshop, are provided in Sections 3 and 4. General comments also made on the modes of failure and monitoring, and the measuring methods in response to the questionnaire are provided here:

- geotechnical modes of failure in general, and internal erosion, degradation of fill and erosion-induced slope failure in embankment dams in particular;
- geochemical modes of failure;
- rate of deformation;
- correlating hazards and modes of failure;
- guidance on pipes and valves;
- hazards or threats such as vandalism and terrorism;
- masonry spillways;
- seepage and piping;
- seasonal effects, such as shrink–swell of clay in core or fill;
- vegetation management;
- sparse data requires a concise user manual on both concrete and embankment dams;
- better overview of the Environment Agency's *Post-incident report*s.

The answers focused on the following aspects of monitoring, which need to be considered for further developments:

- computer modelling, processing, evaluation and presentation of readings;
- zonal techniques (for example, temperature probes);
- reliable dipmeters and seepage monitoring;
- real-time monitoring (for example, telemetry), but one answer which stated that this could be a dangerous trend and that it should not replace site visits;
- triggered alarms;
- remote-sensing techniques (for example, laser sensing, satellites, LiDAR, aerial photos, etc.);
- a comprehensive reference that links hazard and modes of failure to monitoring techniques;
- chemical analysis of drainage flows;
- electro-levels in concrete dams;
- leakage detection;
- methods to measure surface cracking in embankment dams;
- standard inspection guidance to be used by panel engineers;
- several comments were made on the importance of manual readings and site inspections and the dangers of relying on instrumental and remote readings.

Answers as to the further guidance required focused on:

- 'good practice' handbook or guide;
- interpreting electronic readings;
- informed incident database;
- monitoring frequency;
- trigger levels;
- instrument design life;
- reliability of techniques;
- dams and reservoirs magazine;

- techniques database;
- rate of settlement;
- key indicators and associated problems;
- a single unified guide.

Appendix E

Proposals for future research and development projects

MODES OF DAM FAILURE AND MONITORING AND MEASURING TECHNIQUES

PROPOSALS FOR FUTURE RESEARCH PROJECTS

Section 1 Background

In this section, briefly explain the need or opportunity, how the project links to agreed strategies, programmes, business plans and who the key stakeholders are.
Reservoirs and Ecological Hazards: A Best Practice Guide to the Management of Animals and Vegetation This project has been identified as a recommendation in the Scoping Study on 'Modes of Dam Failure and Monitoring and Measuring Techniques'. While it does not form part of the Defra Reservoir Safety Research and Development Strategy, the prioritised list of projects within the strategy must be taken into consideration when delivering this research. The hazards of animal activity and vegetation have been identified within the Scoping Study. These may lead to the development of failure mechanisms within dams and should also be the focus of monitoring and surveillance. The scoping study has identified that, although information on both these hazards is available to reservoir professionals, this is out-dated and does not take into consideration current legislation and recent research. A new document is recommended and this should seek to include guidance relating to both these hazards as follows: • Best practice vegetation management for reservoirs; • Best practice management of animals; • Protected species and habitats; • Statutory consultations and legislation; • Ecological calendar and implications for physical works; and • Case studies.

Section 2 Objectives

*In this section, clearly state what the project is seeking to achieve. All Objectives must be SMART (**S**pecific, **M**easurable, **A**chievable, **R**elevant, **T**ime bound).*	
Key Objective	S – Provide a clear guidance document for multiple-users within the reservoir profession. M – Engage stakeholders in review process to ensure document is clearly understood. A – Much of guidance already exists within ecological community and just needs collating. R – Identified as high priority requirement in the consultation carried out as part of the scoping study. T – Suggested delivery within 12 months of date of issue of the scoping report.

Section 3 Consultation

Briefly outline who should be consulted as part of the research and why.
Environment Agency Reservoir Safety team Environment Agency ecologists and environmental scientists Environment Agency legal advisors Natural England Reservoir Owners and operational representatives Reservoir Managers All Reservoir Panel Engineers (under the Reservoirs Act 1975) Supervising Engineers (under the Reservoirs Act 1975) Representatives from Local Authorities and/ or other bodies responsible for Biodiversity Action Plans Environmental and Engineering Consultants (NEECA2) and contractors (NCF2)

MODES OF DAM FAILURE AND MONITORING AND MEASURING TECHNIQUES

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Section 1 Background

In this section, briefly explain the need or opportunity, how the project links to agreed strategies, programmes, business plans and who the key stakeholders are.
Reservoir Safety: A Checklist for Surveillance This project has been identified as a recommendation in the Scoping Study on 'Modes of Dam Failure and Monitoring and Measuring Techniques'. While it does not form part of the Defra Reservoir Safety Research and Development Strategy, the prioritised list of projects within the strategy must be taken into consideration when delivering this research. The importance of surveillance has been identified within the scoping study. Surveillance is essential both to monitoring of performance and as an indication of potential failure mechanisms developing. An understanding of hazards and modes of failure, as identified in the scoping study, is a fundamental part of surveillance, which in turn is an essential part of risk assessment and risk management. During the study a number of hazards have been identified, along with indicators of failure. The scoping study has identified that, although there is a wealth of information available on hazards, there is not a clear document, which provides information on what should be checked on site. This includes both indicators, which could be monitored, and visual observations of processes. Visual surveillance will remain a key component of identifying progression towards a risk of failure. A new document is recommended. This should seek to build on the work completed as part of the scoping study, providing clear, definitive descriptions of the different hazards and failure modes and commenting on failure process, links to indicators (that in turn reflect upon visual inspection and monitoring equipment) and including diagrams and photos. The document should form a checklist for those responsible for carrying out surveillance of reservoirs. This guide should also aim to provide a useful basis for identifying potential failure modes for individual dams.

Section 2 Objectives

*In this section, clearly state what the project is seeking to achieve. All Objectives must be SMART (**S**pecific, **M**easurable, **A**chievable, **R**elevant, **T**ime bound).*	
Key Objective	S – Provide a clear guidance document for multiple-users within the reservoir profession. M – Engage stakeholders in review process to ensure document is clearly understood. A – Much of guidance already exists within the reservoir community and just needs collating. R – Identified as high priority requirement in the consultation carried out as part of the scoping study. T – Suggested delivery within 12 months of date of issue of the scoping report.

Section 3 Consultation

Briefly outline who should be consulted as part of the research and why.
Environment Agency Reservoir Safety team Environment Agency ecologists and environmental scientists Reservoir Owners and operational representatives Reservoir Managers All Reservoir Panel Engineers (under the Reservoirs Act 1975) Supervising Engineers (under the Reservoirs Act 1975) Representatives from Local Authorities and/ or other bodies responsible for Biodiversity Action Plans Environmental and Engineering Consultants (NEECA2) and contractors (NCF2), in particular to include geotechnical engineers/ engineering geologists, environmental and ecological specialists and civil/ structural engineers

MODES OF DAM FAILURE AND MONITORING AND MEASURING TECHNIQUES

PROPOSALS FOR FUTURE RESEARCH PROJECTS

Section 1 Background

In this section, briefly explain the need or opportunity, how the project links to agreed strategies, programmes, business plans and who the key stakeholders are.

Modes of Failure of Dams – Trial Risk Assessment

This project has been identified as a recommendation in the Scoping Study on ‘Modes of Dam Failure and Monitoring and Measuring Techniques’. While it does not form part of the Defra Reservoir Safety Research and Development Strategy, the prioritised list of projects within the strategy must be taken into consideration when delivering this research.

A considerable amount of work has been undertaken on risk assessment of dams and the scoping study on modes of failure of dams, and monitoring and measuring techniques, feeds into the risk assessment process.

A number of suggestions have been made both in a scoping study on risk assessment and in this scoping study regarding procedure for risk assessment of dams. It is essential that a robust method is defined for the reservoir community. This will become ever more important as the draft Flood and Water Management Bill is implemented.

A trial risk assessment is recommended to support the risk assessment projects currently underway or planned, in particular SC090001 Risk Assessments of Reservoirs. A suitable dam should be chosen and risk assessment carried out, utilising a number of different methods as identified within this scoping study and within the existing risk assessment reports, completed as part of the strategy. The trial should seek to combine hazards, which are present at the site, and develop both an event tree and a fault tree to determine suitability and ease of use. The trial should include worked examples using approaches adopted elsewhere and should include consultation with those responsible for and interested in reservoir safety of the site, including but not limited to those listed in Section 3 below.

Section 2 Objectives

*In this section, clearly state what the project is seeking to achieve. All Objectives must be SMART (**S**pecific, **M**easurable, **A**chievable, **R**elevant, **T**ime bound).*

Key Objective	S – Undertake a rigourous trial of the risk assessment process on a trial site. M – Engage stakeholders to ensure source-pathway-receptor (or equivalent) are fully understood and results are ‘sense-checked’. A – Much work has already been undertaken on risk assessment. R – Risk assessment is identified as high priority in the Defra strategy but the approach has not yet been fully tested and agreed upon by reservoir professionals. T – Suggested delivery within 12 months of date of issue of the scoping report.

Section 3 Consultation

Briefly outline who should be consulted as part of the research and why.
Environment Agency Reservoir Safety team Environment Agency ecologists and environmental scientists Natural England Reservoir Owners and operational representatives Reservoir Managers Landowners and asset owners in the vicinity of the trial site All Reservoir Panel Engineers (under the Reservoirs Act 1975) Supervising Engineers (under the Reservoirs Act 1975) Environmental and Engineering Consultants (NEECA2) and contractors (NCF2) Consultants involved in the production of previous and on-going risk assessment projects identified in the Defra strategy Academic specialists in risk assessment International representative(s), for example from the US, where similar work has been undertaken (see scoping study for details)

MODES OF DAM FAILURE AND MONITORING AND MEASURING TECHNIQUES

PROPOSALS FOR FUTURE RESEARCH PROJECTS

Section 1 Background

In this section, briefly explain the need or opportunity, how the project links to agreed strategies, programmes, business plans and who the key stakeholders are.
Monitoring Techniques for Different Indicators This project has been identified as a recommendation in the Scoping Study on 'Modes of Dam Failure and Monitoring and Measuring Techniques'. While it does not form part of the Defra Reservoir Safety Research and Development Strategy, the prioritised list of projects within the strategy must be taken into consideration when delivering this research. Many of the techniques used for assessing the performance of embankment dams are widely documented and understood. However, these do not cover all the hazards and indicators identified in this scoping study and further research is required to determine which techniques could be adopted and which are not yet utilised by the reservoir community. A consultation exercise is recommended with instrumentation providers to determine suitability for use in embankment dams. This should include retrofitting as well as installation during construction. The project should deliver a report, linking techniques to indicators (and hazards/ modes of failure where appropriate) and should be based on the framework identified in the scoping study (see Table A.3).

Section 2 Objectives

*In this section, clearly state what the project is seeking to achieve. All Objectives must be SMART (**S**pecific, **M**easurable, **A**chievable, **R**elevant, **T**ime bound).*	
Key Objective	S – Provide a clear guidance document for multiple-users within the reservoir profession. M – Engage stakeholders in review process to ensure document is clearly understood. A – Much of guidance already exists within geotechnical community but needs collating and checking for suitability of use within the reservoir environment R – Identified as high priority requirement in the consultation carried out as part of the scoping study. T – Suggested delivery within 12 months of date of issue of the scoping report.

Section 3 Consultation

Briefly outline who should be consulted as part of the research and why.
Environment Agency Reservoir Safety team Reservoir Owners and operational representatives Reservoir Managers All Reservoir Panel Engineers (under the Reservoirs Act 1975) Supervising Engineers (under the Reservoirs Act 1975) Engineering Consultants (NEECA2) and site investigation contractors (NSIF2) Manufacturers and suppliers of standard and bespoke instrumentation

MODES OF DAM FAILURE AND MONITORING AND MEASURING TECHNIQUES

PROPOSALS FOR FUTURE RESEARCH PROJECTS

Section 1 Background

In this section, briefly explain the need or opportunity, how the project links to agreed strategies, programmes, business plans and who the key stakeholders are.
Risk Management of Reservoirs – A Best Practice Guide This project has been identified as a recommendation in the Scoping Study on 'Modes of Dam Failure and Monitoring and Measuring Techniques'. While it does not form part of the Defra Reservoir Safety Research and Development Strategy, the prioritised list of projects within the strategy must be taken into consideration when delivering this research. A considerable amount of work has been undertaken on risk assessment of dams and the scoping study on modes of failure of dams, and monitoring and measuring techniques, feeds into the risk assessment process. A number of projects have been identified in the Defra strategy and in this scoping study, which relate to risk assessment. During recent discussions within the reservoir community on risk assessment tools, it has become increasingly apparent that 'one size does not fit all'. For smaller reservoir owners, the type of risk assessment that will prove viable will be different to that for larger owners. This effect will be even more apparent as the draft Flood and Water Management Bill is implemented and the number of smaller reservoir owners is increased. Following work on risk assessment, a guide is recommended to explain to the reservoir owner, and those responsible for reservoir safety, how reservoirs should be managed. The guide should seek to include the principles of risk assessment, but also summarise results of all other relevant projects being undertaken as part of the strategy. These will include updated guides on monitoring, checklist for surveillance and definition of threats, hazards and modes of failure. The report should provide full reference to best practice guidance produced as part of the strategy and should also aim to provide guidance on asset management in general. Case studies should be included.

Section 2 Objectives

*In this section, clearly state what the project is seeking to achieve. All Objectives must be SMART (**S**pecific, **M**easurable, **A**chievable, **R**elevant, **T**ime bound).*	
Key Objective	S – Provide a clear guidance document for multiple-users within the reservoir profession. M – Engage stakeholders in review process to ensure document is clearly understood. A – Many of the procedures are in place, but need updating and revising in line with new guidance on risk assessment. R – Identified as high priority requirement in the consultation carried out as part of the scoping study. T – Suggested delivery within 24 months of date of issue of the scoping report.

Section 3 Consultation

Briefly outline who should be consulted as part of the research and why.
Environment Agency Reservoir Safety team Environment Agency ecologists and environmental scientists Reservoir Owners and operational representatives Reservoir Managers All Reservoir Panel Engineers (under the Reservoirs Act 1975) Supervising Engineers (under the Reservoirs Act 1975) Environmental and Engineering Consultants (NEECA2) and contractors (NCF2), in particular to include geotechnical engineers/ engineering geologists, environmental and ecological specialists and civil/ structural engineers Academic and industrial asset management specialists

MODES OF DAM FAILURE AND MONITORING AND MEASURING TECHNIQUES

PROPOSALS FOR FUTURE RESEARCH PROJECTS

Section 1 Background

In this section, briefly explain the need or opportunity, how the project links to agreed strategies, programmes, business plans and who the key stakeholders are.
Reservoir Engineering Design to Eurocodes: Draft Guide for Consultation This project has been identified as a recommendation in the Scoping Study on 'Modes of Dam Failure and Monitoring and Measuring Techniques'. While it does not form part of the Defra Reservoir Safety Research and Development Strategy, the prioritised list of projects within the strategy must be taken into consideration when delivering this research. BSI British Standards has published a list of 57 structural design codes it plans to withdraw in March 2010. The majority have been superseded or made obsolescent by Eurocodes. The list includes all or most parts of well-known standards such as BS 8002 for earth retaining structures, BS 5400 for bridges, BS 5628 for masonry, BS 5950 for steel, BS 6399 for loading, BS 8004 for foundations, BS 8100 for towers and masts and BS 8110 for concrete. BSI is obliged to withdraw all standards that have the same scope and field of application covered by the Eurocodes. Those partly covered by Eurocodes will be amended or revised to delete conflicting requirements and reflect the changed scope. British standards are well understood by the reservoir community and are either referred to specifically in key documents identified in the scoping study, or have been used to adopt an appropriate methodology for analysis. Eurocodes differ in their approach and work is required by the industry to understand the implications. This will affect both design of new elements and assessment of the integrity of aging infrastructure. An example of this is acceptable factors of safety for embankment slopes under normal loading conditions, seismic loading and under rapid drawdown. The relevant geotechnical Eurocode 7 does not adopt a factor of safety approach and therefore work is required to understand what will be acceptable under the new guidelines. A document is required to summarise the key implications of the Eurocodes for reservoir engineering design. Where differences exist for commonly assessed elements, such as embankment slopes, a comparison between previous and new methods should be provided, with worked examples where appropriate. As Eurocodes are still being implemented by designers, it is recognised that not all aspects of reservoir engineering design will yet have been tested with Eurocodes. The Eurocode partners should be engaged as necessary to ensure that the recommendations provided in the codes are fully understood.

Section 2 Objectives

*In this section, clearly state what the project is seeking to achieve. All Objectives must be SMART (**S**pecific, **M**easurable, **A**chievable, **R**elevant, **T**ime bound).*	
Key Objective	S – Provide a clear draft guidance document for consultation with stakeholders listed in Section 3. M – Engage stakeholders in review process to ensure design methods are robustly tested. A – Many of the design processes for reservoirs well understood, but need updating to reflect new approaches adopted in Eurocodes. R – Identified as high priority requirement in the consultation carried out as part of the scoping study. T – Suggested delivery within 24 months of date of issue of the scoping report.

Section 3 Consultation

Briefly outline who should be consulted as part of the research and why.
Environment Agency Reservoir Safety team Reservoir Owners and operational representatives Reservoir Managers All Reservoir Panel Engineers (under the Reservoirs Act 1975) Supervising Engineers (under the Reservoirs Act 1975) Environmental and Engineering Consultants (NEECA2) and contractors (NCF2), in particular to include geotechnical engineers and civil/ structural engineers Academic and industry leaders in engineering design Representatives from the Institution of Civil Engineers Representatives from the Eurocode partners

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