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Environment Agency

Scoping research to improve dam and levee breach prediction

Flood and Coastal Erosion Risk Management Research & Development Programme

Research Report

Date: March 2023

Version: FRS17071/R

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This report is the result of research commissioned and funded by the Joint Flood and Coastal Erosion Risk Management Research and Development Programme. The Joint Programme is jointly overseen by Defra, the Environment Agency, Natural Resources Wales and Welsh Government on behalf of all risk management authorities in England and Wales: Flood and Coastal Erosion Risk Management Research and Development Programme

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Dr Robert Bradburne
Chief Scientist

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Executive summary

When a dam or levee collapses and the contained water escapes, this is termed a breach, with the size of flow and time to peak flow depending on the properties of the levee (such as soil type or zoning) and the hydraulic loading conditions. Peak flow can vary by orders of magnitude. For example, peak breach flows from a well-compacted clay embankment may be only 1% of the peak flow from loose silt or sand embankments.

The processes that occur during a breach are complex and combine hydraulic, soil erosion and structural behaviour processes. They are closely linked during the breaching process. Hence even small changes in any of these aspects can change how the breach evolves, and whether there is complete collapse (breach), or just damage to the levee with no escape of the contained water. Section 2 provides a summary of the processes, showing which process stages are likely to be of most interest to different end users.

Predicting the timing and magnitude of peak breach flow and estimating the water volume released are an integral part of a risk-based approach to managing flood risk. Section 5 describes user needs and explains the need for:

- asset owners to understand how to use grass maintenance and other techniques to slow the initiation of breach and prolong the time before complete collapse
- incident managers, and their technical advisors, to understand the processes involved, and thus the time a breach is likely to take to develop, from initial damage through to complete collapse of the bank and release of the retained water
- emergency planners to understand the extent and timing of downstream flooding, which is governed by the timing and magnitude shown on the hydrograph, to be able to plan effective warning and evacuation
- policy and decision makers to understand the risk associated with different assets, and what steps could be taken to reduce these risks

The purpose of this scoping report is to clarify:

- the processes that occur
- the tools that are available and used to predict breach flow
- our current state of knowledge and critical research gaps
- the case to justify the research needed

The result is a road map aimed at producing the tools that users need to apply breach prediction methods more consistently and appropriately.

We cover issues and perspectives from both the reservoir safety and wider flood risk management communities, with the aim that the issues, conclusions and recommendations we produce are applicable across all sectors.

Although applicable to any soil-based levee or dam, the focus of this study has been on inland structures, rather than those at the coast, subjected to wave action.

Our main conclusions are that:

- there is no internationally agreed standard test method to measure erodibility, or the erosion resistance of a grass cover layer
- breach of cohesive (e.g. silts, clays) homogeneous embankments is reasonably well understood, with software available to model this behaviour, but breach involving coarser-grained materials and zoned embankments is not as well understood, with no internationally validated methods of modelling this
- there is poor understanding of how the dominant erosion processes change through the various stages of breach development and of the tools to model development rate accurately, especially for internal erosion
- the techniques available to model breach, and associated uncertainties in interpreting the output, are not well understood by the UK engineering community
- there is a lack of published reliable data on erodibility of UK soils, and how this should influence asset management in the UK

This means that it is not currently possible to reliably estimate the timing and peak flood flows after a dam or levee collapses (breach). This compromises estimates of current flood risk, effective emergency planning and asset management strategy.

The current annual cost of maintaining existing, and building new, dams and levees is around £950 million per year, of which around 43% is new build, 45% is upgrade/repair of existing assets and 12% is operating expenditure (OPEX), including forecasting. Based on this the benefits of the proposed research are estimated at £4 million per year, from better identification of the existing assets that would benefit from an upgrade and approximately £0.5 million per year on reduced operating costs (OPEX). The benefit estimates were based on expert judgement of the potential reduction in risk to life from improving breach hydrograph estimates and the timeliness of triggered actions to response in an incident. The benefits reflect both this and a consideration of improved asset management. The estimated overall benefit:cost ratio of undertaking research in this field is over 10, confirming it is a valued area in which to progress.

Possible actions

We identify a series of actions that could address the conclusions described above. They comprise:

Guidance

3 actions. These are relatively small actions to provide guidance to practitioners while we follow the wider programme of research.

Erodibility parameters and dominant processes

6 actions. The first 5 of these are the highest priority. Four focus on better understanding the different aspects of soil erodibility, which are fundamental processes driving breach initiation and formation processes. The fifth addresses the need to define a measure of grass cover performance, which would support later progression of our ongoing grass and soil erosion project.

Refining breach models

6 actions. These address model performance and development, covering internal erosion for simple structures and then both internal and surface erosion for zoned structures. The actions logically follow completion of the earlier action to understand dominant erosion processes.

Refining specific aspects

7 actions. Work to understand the performance of grass cover and grass reinforcement systems develops the results of earlier actions. The other actions address individual issues and can be undertaken independently.

Future modelling approaches

This is a longer-term goal that is likely to evolve through further academic research and development work.

Vision

By producing this report, and the associated road map for action, the vision is:

- That in approximately ten years' time the science and engineering tools relevant to UK dams and levees will have improved substantially and contribute to managing all forms of flood risk. In addition, the engineering professions and others involved in managing water-retaining assets will have a better and more consistent understanding of breach processes and be applying these in their management of all forms of built infrastructure.

Disclaimer

This research report seeks to reflect best practice at the time of issue. When applying any conclusions or outputs from the report (as part of a wider-risk based approach), you will always need to consider the impact of any more recent research or developments.

None of the conclusions or outputs in this report are prescriptive. Each site and situation will be unique and you will need to apply considerable judgement to assess and identify an appropriate, risk-based approach for each project.

Occasionally this report uses best expert judgement, where exact costings are unknown. These are often conservative in estimate and intended as a good guide. These types of estimates may require further refinement if considering their use in wider applications.

The research proposals and programme identified is meant as an aid to support future research and is not prescriptive in its application. It is expected that ongoing developments and opportunities may present themselves in helping to adapt and take forward research in this field.

Acknowledgements

This report has been drafted by Mark Morris and Alan Brown, who are both members of the Institution of Civil Engineers (ICE) Reservoir Safety Research Advisory Group (ReSRAG), an advisory committee to the ICE on research matters on reservoir safety.

Mark Morris works for HR Wallingford and has over 30 years' experience of research and specialist consultancy in flood risk analysis and management. He has a PhD in breach modelling and over the last 20 years has worked on various research and consultancy projects, including European and wider international collaboration projects, investigating the various aspects of breach formation and developing modelling solutions for industry use.

Alan Brown has a first degree in Engineering from Peterhouse, Cambridge, and an MSc in Soil Mechanics from Imperial College. He was Discipline Lead for dams and hydraulic structures at Jacobs from 2005 to 2012, was Technical Director at Stillwater Associates until 2019, and has now re-joined Jacobs. He has been on the All Reservoirs Panel under the Reservoirs Act since 2001 and has led in developing a risk-based approach to dams (and levees) in UK, including being a lead author of both the Interim Guide to Quantitative Risk Assessment for UK Reservoirs (2004) and Risk Assessment for Reservoir Safety Management (RARS) (2013). He has been a construction engineer for 18 new flood storage and irrigation reservoirs and carried out over 200 ten-yearly Section 10 safety reviews of existing dams, both of which have included screening-level breach and consequence assessment.

The report has also built on consultation with and review by experts in the flood risk management and reservoir safety sectors listed below. This report is the authors interpretation of these discussions. This includes members of the Reservoir Safety Research Advisory Group, ReSRAG:

- Tracey Williamson, Past BDS chair, ReSRAG past chair and Arup
- Chrissy Mitchell, Environment Agency
- Owen Tarrant, Environment Agency;
- Tony Deakin, Environment Agency
- Jaap Flikweert, Royal HaskoningDHV
- Fola Ogunyoye, Royal HaskoningDHV
- Ben Gouldby, HR Wallingford
- Jonathan Simm, HR Wallingford
- Claire Hollingsworth, Environment Agency

1. Introduction

1.1. Background

Predicting breach often forms a critical part of the risk assessment associated with asset management, which in turn provides underpinning data for a range of activities. These include asset design, asset management, spatial planning and flood risk management, plus incident management and emergency planning (Figure 1). Breach prediction can provide a range of data, such as the likelihood of failure and the timing and magnitude of flood flows and potential breach dimensions. The likelihood of damage, likelihood of breach, and different stages of breach development are of greater or lesser interest to different end users, depending upon their need and role within the professional community (Morris and Hughes, 2008). For example:

- **a designer** is interested in producing a design that will perform according to the project specifications, for example, withstanding certain magnitude flood events without failure
- **an asset manager** is interested in the initial breaching process and indicators of this, so as to be able to avoid development of a catastrophic breach
- **a spatial planner** is interested in potential flood conditions that might arise from a breach (such as flood hazard/life safety, potential access and egress routes, zoning of appropriate development)
- **a flood risk manager** is interested in what might happen under a range of different load conditions and during a catastrophic event, so as to be able to plan for all eventualities, and also as a means of designing decision-making support for an emergency
- **an incident manager** is interested in all stages of the breach process to be able to advise on the safety of a structure during an incident and on the likelihood, timing and management (including repair) of any potential catastrophic failure.

The likelihood of breach initiation can be assessed by developing fragility curves. While these are an integral part of flood risk analysis and breach-related modelling, the assessment of fragility curves is not within the scope of this report, which focuses on breach process modelling.

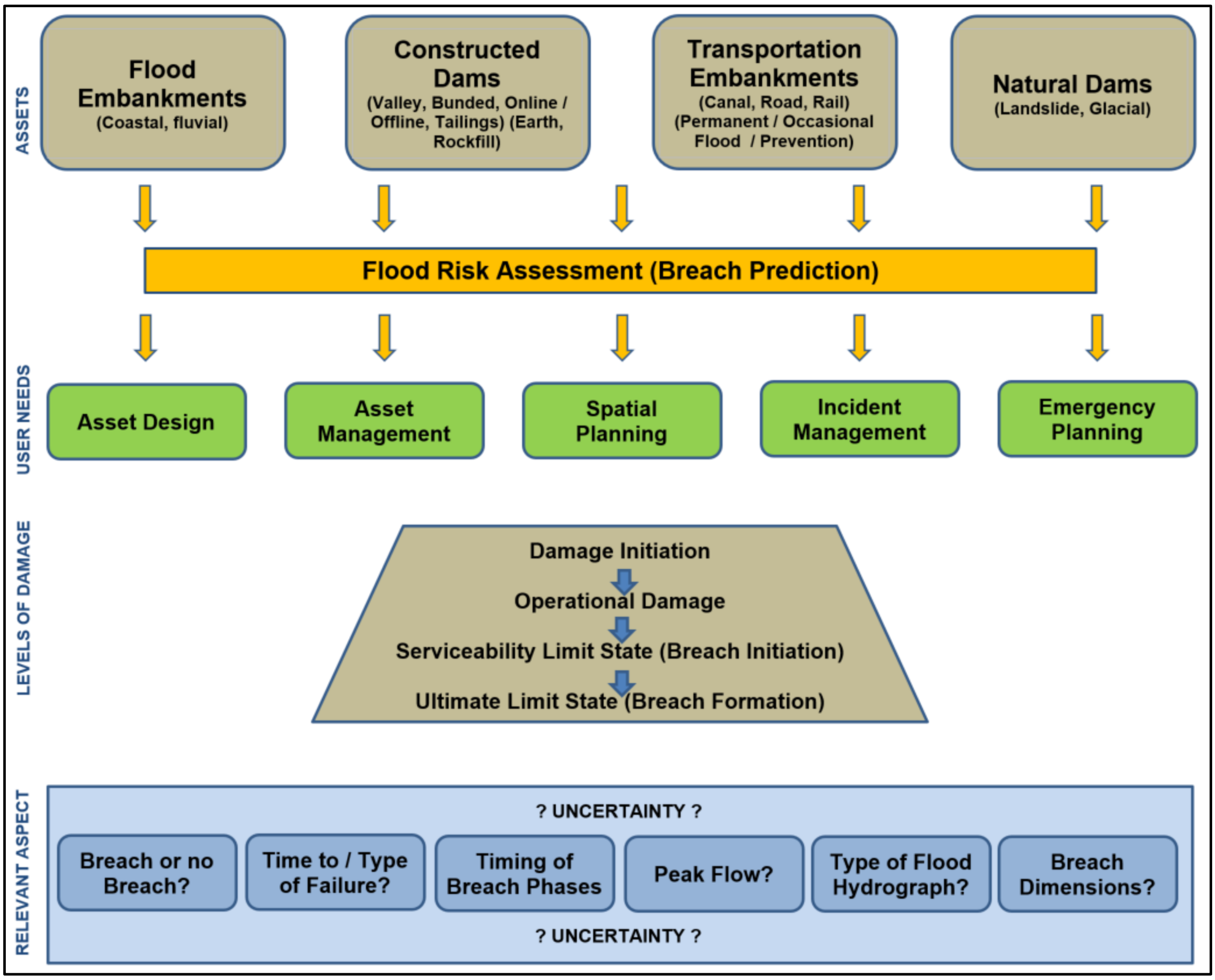


Figure 1 - The role of breach prediction within flood risk analysis and management

The boxes at the bottom of the diagram in Figure 1 give an example of the questions that the various end users of breach prediction data are likely to ask. In addition to these is the underlying question of uncertainty. The complex interactions that occur during the breaching process lead to considerable uncertainty in the predicted results (Morris, Kortenhaus and Visser, 2009). The fact that the prediction of breach occurring forms one part within an overall flood risk assessment, and attention is often focused on inundation planning, can mask very approximate and uncertain estimations of the breach condition itself (Environment Agency, 2009).

We consider 3 different perspectives to help understand breach processes and prediction, namely:

- defining damage levels and the potential risks arising from different levels of damage (Section 1.2)
- understanding the triggers leading to breach (Section 1.3) and how the physical characteristics of the dam or levee (including the hydraulic conditions) affect the breaching process (Section 1.4)
- understanding the breach physical processes themselves (Section 1.5)

This introductory chapter closes with an overview of the significance for breach of the size of UK dams and levees (Section 1.6).

1.2. Defining damage and the potential risks arising from different levels of damage

It is helpful to define the amount of damage to a structure during the breaching process, as different users are likely to be interested in different stages of damage. Table 1 below shows the definitions used for this research.

The significance of the damage that occurs to dams and levees during the breach initiation phase also depends on the nature of further breach initiation and formation processes on that particular structure.

For example, where breach initiation is via internal erosion, it is often difficult to assess how close the situation is to the start of breach formation (that is, the point where flow starts to increase rapidly). The extent and location or route of internal erosion is often unclear until more significant indicators appear, such as crest or surface subsidence and a notable progressive increase in erosion flow.

In overflow or overtopping conditions, the surface layer may be destroyed – comprising grass, rock, stone or geotextile covering. The rate at which erosion then affects the breach flood flow depends on the erodibility of the soil. When headcut occurs, the breach flow typically remains low until the headcut cuts through the crest, after which catastrophic failure is imminent. When surface erosion occurs, the crest typically erodes down in parallel with surface erosion and retreat, and hence the breach flow increases progressively from the point that erosion starts. Where the structure is more complex – perhaps with a core wall of some sort – catastrophic failure can occur quickly after erosion and removal of downstream supporting material, leading to the structural failure of the core wall and catastrophic breach.

Therefore, to evaluate the significance of any erosion damage we need to understand the overall structure design and anticipate the way in which breach erosion might progress given the type and state of particular materials and their susceptibility to erosion.

Consequently, the failure of grass surface protection on an embankment constructed from erosion-resistant clay will be of concern in terms of damage, but will not pose an immediate threat of catastrophic breach. Headcut erosion – most likely initiating near the toe or at transition points on the landside face – will need to form and progress towards the crest before raising concerns of potential catastrophic failure.

However, the failure of grass cover on an embankment constructed from loose sandy soil and gravel would be of much greater concern Erosion of the soil is likely to be fast once the grass protection is lost, and erosion would also be likely to lower the crest simultaneously to the downstream slope.

Table 1 - Damage levels for application in this research (overtopping erosion)

Breaching process			Description of level of damage		End user/interest
Stage		**Damage level at end of stage**	**Overflow erosion**	**Internal erosion**	
1a	Initiation	No damage	No damage to surface soil layer	No damage	
1b		First damage	Small/single area of damage of grass cover and local erosion (within soil root zone) For reinforcement products, some reinforcement exposed	Initiation	Asset manager: - What repair or maintenance operations are required?
1c		Perforation of cover layer	Perforation of grass cover with erosion to base of soil roots (nominally 300 mm) For reinforcement products, perforation of reinforcement and removal of soil from beneath (For structures with sacrificial cover, loss of majority of cover)	Continuation if no filters: start of concentrated leakage	Incident manager: - How long before failure (end Stage 4)? - What can be done to prevent failure? (for example what is happening to lead to failure)
2	Continuation	Major damage (serviceability limit state)	Significant erosion to downstream face of structure (for example, depth at least 20% of crest width)	Progression: leakage sufficient to declare serious incident (and initiate emergency drawdown for reservoirs)	
3	Formation	Erosion affects crest width and/or elevation (ultimate limit state)	Erosion cuts back across crest and reaches upstream slope	Progression: effects of internal erosion reach crest, for example as sinkhole	Probability of failure: Designer, Risk analyst
4	Enlargement	Structure failure	Enlargement of erosion pathway with catastrophic release of retained water		Consequences of failure: Emergency planning, Spatial planners

1The ‘breaching process’ includes various stages such as breach initiation, formation and growth (see Section 2 – Physical processes). As these stages occur, the dam or levee transitions from a stable and apparently normally functioning structure through increasing degrees of damage to catastrophic failure and uncontrolled release of water.

1.3. Triggers leading to breach

While it is a prerequisite for water to be retained by the embankment (whether due to a fluvial or coastal flood, or retained permanently by a reservoir), many different triggers can lead to breach.

These are well described in Step 1a of Risk Assessment for Reservoir Safety (RARS), ‘Failure mode identification’ (Environment Agency 2013a, 2013b), with a similar guidance given in the corresponding chapter of the US Bureau of Reclamation, ‘Best practices and risk methodology’ (USBR, 2015) (see box below).

For the purposes of this report they are subdivided into 2 main groups: ‘External erosion’, covering overflow and overtopping by waves; and ‘Internal erosion’, covering migration of fines within the body or foundation of an embankment.

1.4. Understanding how the physical characteristics of the dam or levee (including the hydraulic conditions) will affect the breaching process

The physical characteristics of the dam or levee affect how the breaching processes develop. These include the design and complexity of embankment construction, the materials used, the quality of construction, the maintained condition and the hydraulic loads. This complex combination of factors can result in multiple potential failure modes, or at least multiple ways in which breach may be initiated, on what are superficially similar dams (externally).

1.4.1. Sources of further information

- ‘The International Levee Handbook’ (ILH) (CIRIA, 2013), Section 3.5 for more information on the complexities of failure, and the processes that can occur from acceptable (dam or levee) performance, through deterioration, partial damage and complete failure. See also Section 8.10 for information on breach.
- Environment Agency report SC080048/R1 ‘Modes of dam failure and monitoring and measuring techniques’ (Environment Agency, 2011a)
- CIRIA report 167 (Hewlett, Boorman and Bramley, 1987)
- Environment Agency report SC080046/R1 ‘Lessons from historical dam incidents’ (Environment Agency, 2011b)
- Guidance on risk management from the US Army Corps of Engineers (USACE)/US Bureau of Reclamation (USBR, 2019) – in particular Chapter IV-1 on the erosion of rock and soil.

For more detailed examples of levee failure mechanisms and good practice for design and maintenance see:

- Environment Agency R&D technical report FD2411/TR1 November 2007 'Management of flood embankments: A good practice review' (Environment Agency, 2007)

1.5. Understanding the breach physical processes

The physical processes can include headcut, surface erosion, internal erosion and slumping (see Section 2). As dams and levees often contain layers of different materials and embedded structures, these processes can change as breach initiation, formation and widening progress.

The complexity of breach prediction has tended to result in fragmented research and uncertainty within industry on the methods available for breach prediction, and when and how to apply them. Since many different end users rely either directly or indirectly on data drawn from breach analyses, this uncertainty has resulted in different solutions being applied for different applications, without a clear understanding of the inherent uncertainties within those solutions.

In addition, since different erosion processes – at both macro and micro scale – can occur in the erosion of different materials (for example, rockfill, sands and gravels and clays each having distinctly different erosion behaviour), the research published often appears to offer a generic solution to 'breach', but in practice relates only to the breaching processes of a specific range and state of material. This can further confuse the user in the selection of the most appropriate solution.

The next section provides a summary of common misunderstandings relating to breach processes and breach prediction.

Table 2 - Common misconceptions and misunderstandings relating to breach

Issue	Misconception	Correction
One (breach) model fits all	All embankments breach in the same way	Different mechanisms will prevail driven by material type, construction and design. Core processes apply to non-cohesive, cohesive and rock fill designs.
Use of simplified breach equations	All embankments breach in the same way	Simplified breach equations will most likely be applicable to a very specific set of test data and hence design of embankment. They should only be used for conditions outside this data envelope while recognising the uncertainty.
Use of peak discharge equations	Provide a simple 'reliable' method of predicting the 'worst case' from a breach	Peak discharge equations have been developed for use in assessing dam failure and are generated by regression analysis using historical dam failure data. The reliability of the equation depends greatly upon the historical data used and specifically the types of dam within the dataset. Typically, no allowance is made for variations in dam condition, design, materials etc.

Issue	Misconception	Correction
Use of peak discharge as a measure of the worst case	The highest peak value from a breach flood hydrograph will match the worst-case condition downstream	When assessing flood conditions arising from a breach, the downstream flood conditions will be a function of the volume of water released, timing and local topography. Selection of the peak discharge value as correlating to the worst conditions downstream is not always appropriate. Analysis of the full breach hydrograph is required for a reliable assessment
Quality of construction	All embankments breach in the same way	The embankment quality and condition arising from construction can significantly affect the rate of erosion and hence breach growth. A measure of material condition should be incorporated in any predictive model.
Embankment condition at failure	All embankments breach in the same way	Weather and hydraulic loading conditions can significantly affect the embankment condition prior to breaching. Extreme and prolonged rainfall or prolonged high-water levels can affect moisture content and hence erodibility. This aspect is also relevant in relation to potential effects of climate change.
Shape of breach growth (side walls)	Predefined breach shapes, such as trapezoidal or parabolic, are used within models to calculate flow through the breach	The shape of the breach opening during growth is a function of material type and erosion process. However, with soil moisture content offering some form of strength through soil suction, both cohesive and non-cohesive breaches tend to develop with vertical side walls.
Flow control (prediction) through a breach	The flow through a breach is controlled by a section within the breach opening (typically used in models)	The point of critical flow through a breach is often across the upstream face of the embankment as the breach forms. Erosion typically creates a curved weir that forms upstream of the central part of the breach. This weir is typically wider than the minimum central section of the breach.
Use of standard 2-D, steady flow sediment equations	Assumption that the erosion of material from a (dynamic) breach follows the same laws as applied to morphological modelling in rivers (ie long-term steady evolution based upon steady flow data)	Breach formation is dynamic and unsteady; morphological river modelling is taken as a long-term averaged process. It is by no means clear that the 2 processes correlate.

1.6. Why vulnerability to rapid breach is important for assessing resilience of UK dams and levees

Vulnerability to rapid breach (eg sand and silt embankments) is important as the dam or levee will fail faster and give higher peak discharges, both of which significantly increase flood risk to life. Embankments that are resistant to breach (eg heavy clay embankments) will take longer to fail, and in some cases, despite suffering overflow damage, may not collapse and release the contained water; allowing time for flood warnings, temporary defences, evacuations and drawdown. Additionally, the peak breach discharge will be lower, with significantly reduced risk to life and property damage. This is illustrated in Figure 2 and Figure 3 (EA Report SC090001/R1 and R2 – 'Guide to risk assessment for reservoir safety management (RARS)' (Environment Agency 2013a, 2013b).

For breach from large dams, of say 10 metres deep and significant velocity, the consequences would be total destruction of property effected downstream and 100% fatality rate. However, where the peak breach discharge is lower, giving smaller flows and velocities, the risk to property and life would be reduced. In respect of the fatality rate, this could be around 1% for lower flows and 100% for high breach flows. This is important in terms of resilience, as embankments that are lower and/ or resilience to rapid breach will result in reduced life loss compared to those which are more vulnerable to breach.

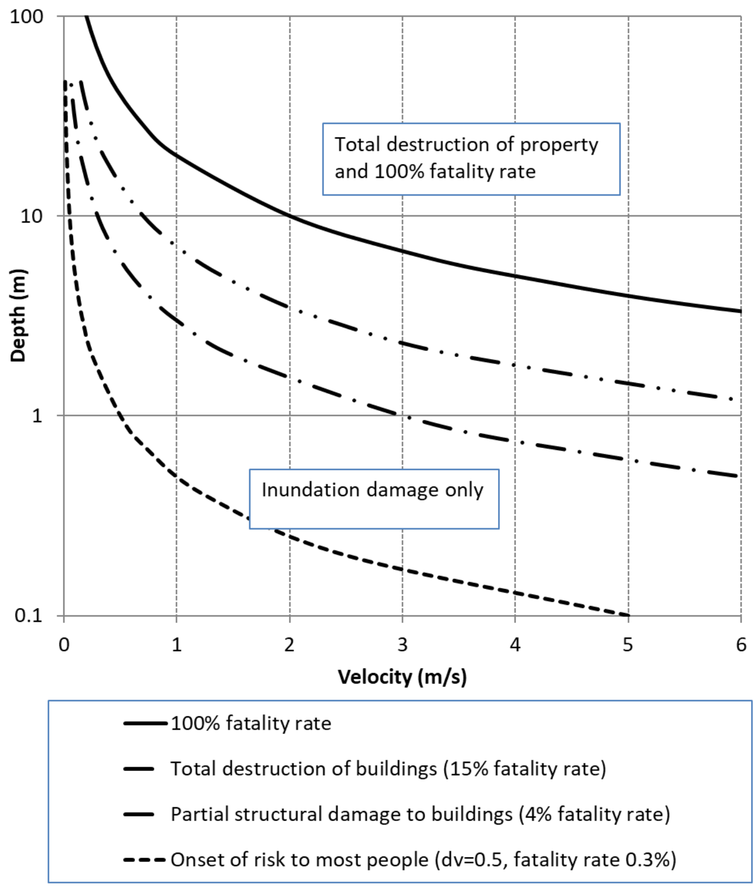


Figure 2 - Variation in property damage and risk to life with depth and velocity of floodwater
Note: dv = dependent variable; m = metre; m/s = metres per second

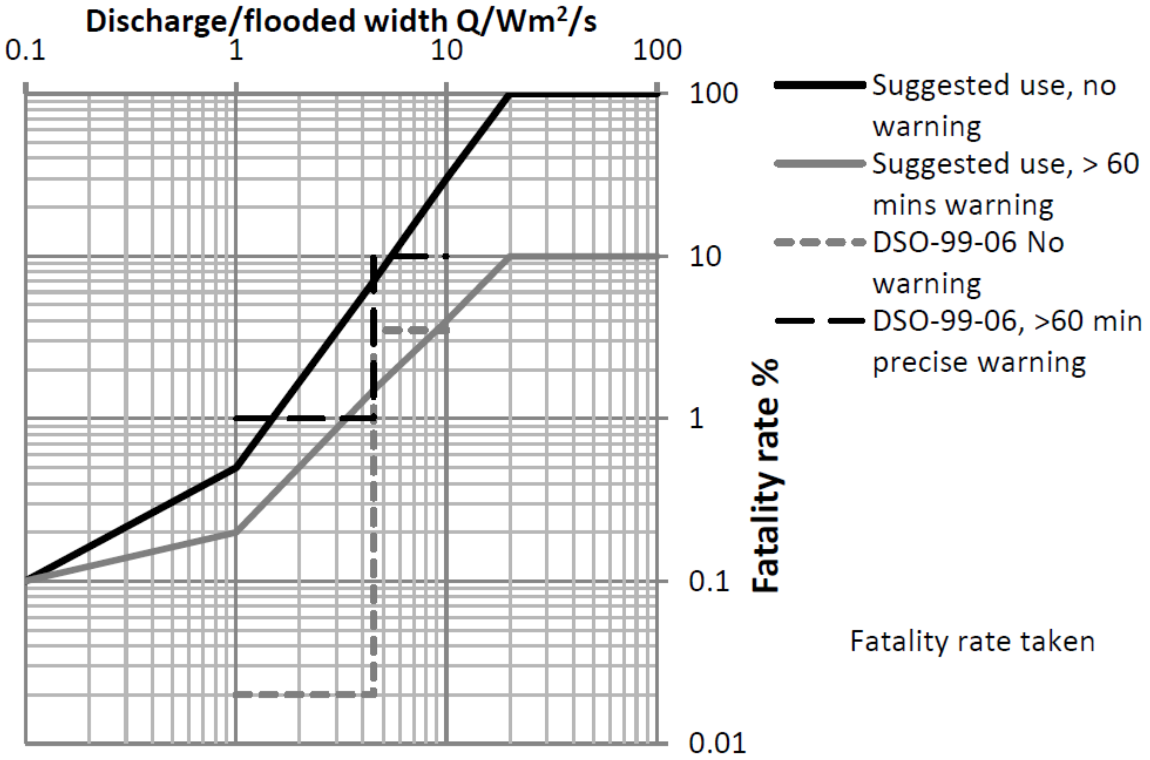


Figure 3 - Likely chance of death (fatality rate) vs size of flood
Note: DSO-99-06, an empirical life loss estimation tool developed by USBR.

Figure 4 plots the range of height and water volume of UK reservoirs under reservoir safety legislation as at 2009, with peak breach flow predicted using the high erodibility equation of Xu and Zhang (2009), which is superimposed. This shows that the range of peak breach discharge varies by 4 orders of magnitude, from a few cubic metres per second (m3/s) for small bunds to over 5,000m3/s. The peak flow for coastal levees would be insensitive to retained volume and so would depend on the height of the levee and width of the breach. Fluvial levees would be between breach flow from coastal levees and dams, as the flow within the river channel may affect breach formation (as it does for canals).

It is important to understand this range of behaviour when scoping breach research, as the scope of any research project needs to be clear on the range of structure size and retained water that it covers.

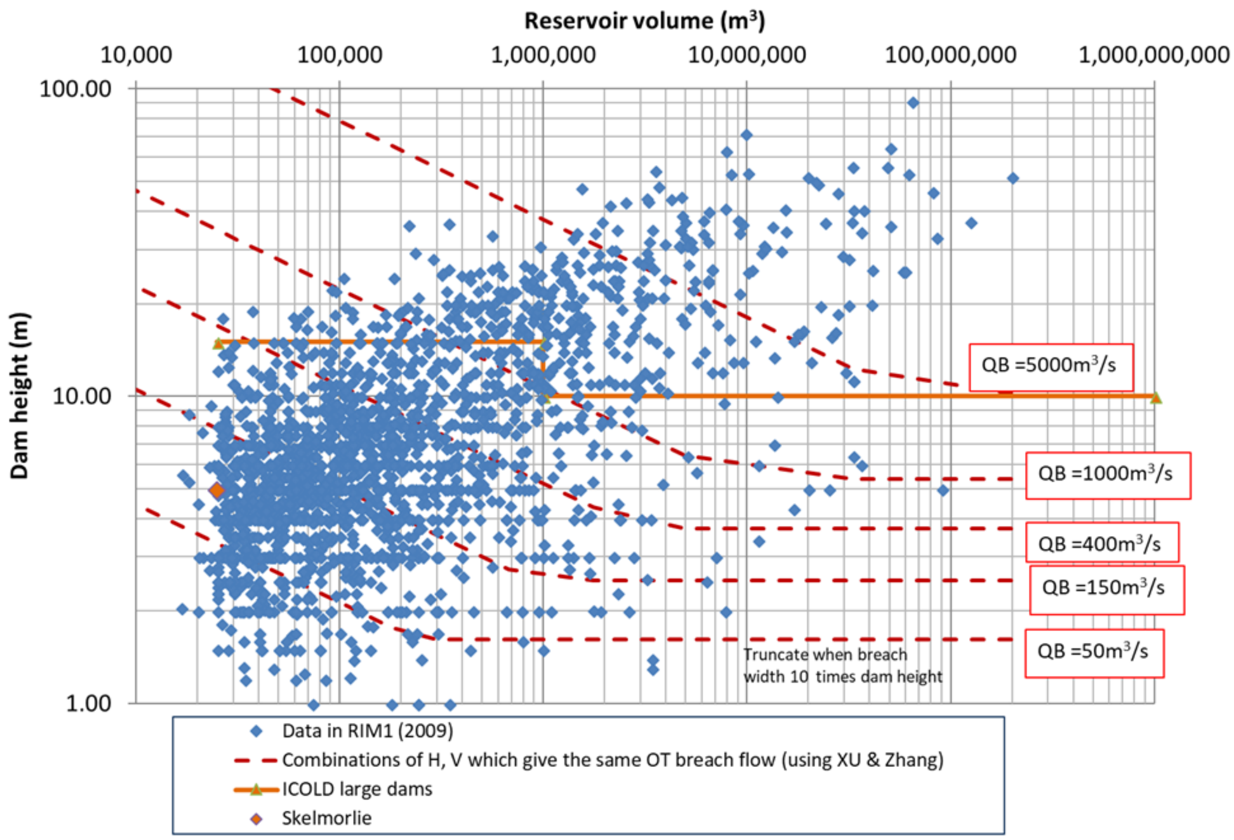


Figure 4 - The range of UK dams by size and consequential range of potential breach discharge
Source: Deakin and others (2016)

1.7. Need for research into breach

This introductory chapter has described some of the physical complexities of the breach process and some of the common misconceptions. It has also described how understanding the process of breach underpins many risk management activities and is relevant to a wide range of end users.

A clear framework is needed showing the different processes and potential solutions for prediction, along with an indication of complexity, the data required and uncertainty in results. This framework should clarify options for predicting potential breach conditions and steer users towards the most appropriate solution(s) for a given situation.

This scoping report now goes on to:

1. clarify the processes that occur in breach (Chapter 2)
2. identify the tools that are available and used to predict breach flow and timing (Chapter 3)
3. establish our current state of knowledge (Chapter 4)
4. provide a road map and case to define research needed to provide users with tools for more consistent and appropriate application of breach prediction methods (Chapter 5)

2. Physical processes

This chapter introduces the different physical processes that can occur during breach formation and how they are interrelated. It explains how the process depends upon the asset (dam or levee) structure and the soil and hydraulic load conditions, and ultimately how these factors affect the way in which breach occurs and hence the rate and characteristics of floodwater released.

2.1. Introduction

The type of erosion process that takes place affects the characteristics of a breach (including the timing and shape of the flood hydrograph). When a breach starts, the type of erosion process is also what the observer will see – hence understanding these processes is important from both an inspection and flood risk analysis perspective.

Many researchers have analysed the breach problem and attempted to define distinct stages in breach development. Whether quoted as stages or phases of development, none of these definitions has universal acceptance, perhaps due to confusion in understanding the different breach processes that can occur when breach forms through different types of material. Appendix A provides one definition of the different stages of breach and how these relate to the breach flood hydrograph.

While a variety of equations have been developed in efforts to predict the rate of erosion of soils, parameters that are common to many relationships include:

- K_d - soil erodibility
- τ - effective shear stress (applied by the water on the soil surface)
- τ_c - critical shear stress (at which soil starts to erode)

Of these parameters, while soil erodibility is a simple concept, many factors can affect it including, for example, soil type, soil grading, moisture content, compaction energy, temperature. A number of different tests exist to measure soil erodibility both in situ and in the laboratory.

The physical processes that occur, from breach initiation, through breach formation and widening, depend upon the type and state of the materials used to build the dam or levee. The differences between the physical processes occur at both macro and micro scales. At a macro scale it means that the shape of the eroding dam or levee, as seen by someone observing the failure process, will differ notably. At a micro scale, the nature and rate of erosion will be controlled by the way in which the material particles are eroded – this is typically reflected in the rate at which macro scale changes are observed.

Examples of different macro scale failure processes are as follows:

Headcut erosion: This typically occurs in clays, which are less permeable and more erosion resistant. Erosion forms steps in the surface, which tend to merge into 1 or 2 large steps that cut back (headcut) into the dam or levee slope. The crest area does not erode until the headcut erodes through to the upstream face of the dam or levee, at which point rapid, catastrophic failure occurs.

Surface erosion: this typically occurs in sands and gravels, which are more permeable and easily eroded by surface flow. Slopes erode uniformly, including the levee or dam crest area, which allows a more progressive release of floodwater (in comparison to headcut failure).

Rockfill slump erosion: this occurs when highly permeable slope material slumps and progressively flattens.

Internal erosion: this occurs when flow develops through the structure (via various processes), which ultimately can lead to full breach via any of the 3 processes above.

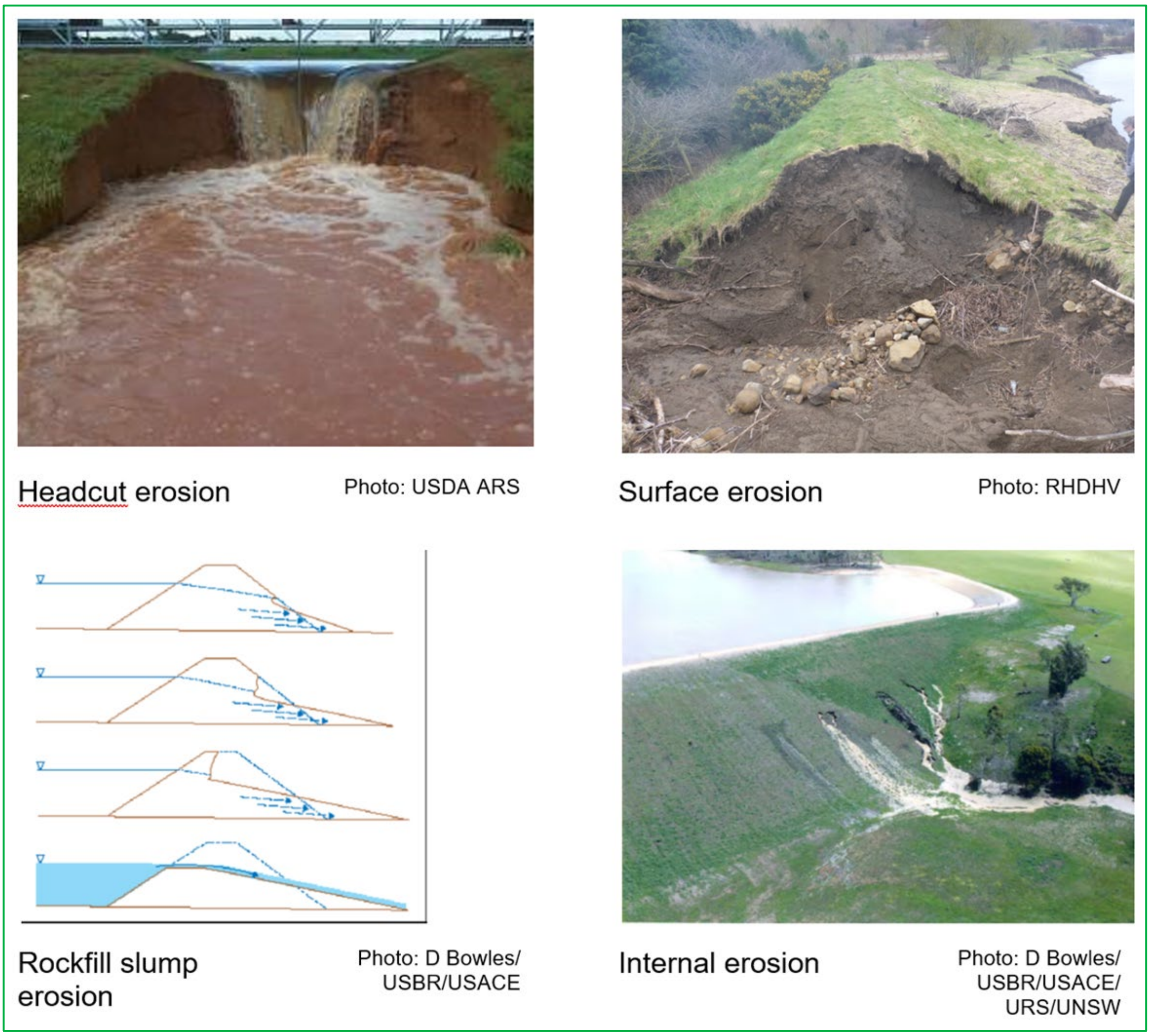


Figure 5 - Main breach initiation and formation processes
Where, RHDHV = Royal HaskoningDHV, UNSW = University of New South Wales, USDA ARS = Agricultural Research Service of the United States Department of Agriculture.

The failure processes and composition of the embankment will govern breach behaviour, whether it is a sudden catastrophic failure, or a progressive failure; these are well illustrated in the International Levee Handbook (ILH) Box 3.1.4 (CIRIA, 2013, page 163).

This chapter now goes on to explain each of these processes in more detail, together with the links between them and how they are affected by the various driving and resisting parameters, and the composition/structure of the dam or levee.

2.2. Headcut erosion

The different stages of headcut driven erosion breach growth are provided here.

Stage 1 – Headcut formation

Erosion of the downstream face by overflowing water leading to the formation of a headcut (step) in the embankment face capable of moving upstream through the embankment to form a breach. Erosion during this stage does not affect discharge across the crest of the embankment.

This stage relates to flow behaviour in the range T1 to T2 in Table 13 , Appendix A.

Figure 6 - Image of headcut formation

Stage 2 – Headcut advance through the embankment crest

The headcut advances upstream cutting through the downstream face of the embankment and into the crest. Prior to cutting through the crest and upstream slope, the headcut still has little effect on discharge over the embankment (and through the breach).

This stage also relates to flow behaviour in the range T1 to T2 in Table 13 , Appendix A.

Figure 7 - Image of headcut advance through the embankment crest

Stage 3 – Breach formation – headcut enters the reservoir

The headcut advances upstream and cuts through the crest and upstream face into the reservoir. This has the effect of lowering the controlling crest elevation into the breach, and hence flow increases significantly. As flow increases, so does the headcut erosion process. At this point the embankment or dam is likely to progress to catastrophic failure. Erosion of the upstream face continues down to or below the base level of the embankment.

This stage relates to flow behaviour in the range T2 to T3 in Table 13, Appendix A.

Figure 8 - Image of breach formation as headcut enters the reservoir

Stage 4 – Breach expansion during reservoir drawdown

Following rapid increase in discharge under Stage 3, the width of the breach then grows because of the reservoir discharge. The rate and extent of growth is affected by the volume of reservoir water that can be released. During this stage of growth, discharge through the breach eventually stops either through the release of all reservoir water, or because downstream flood levels rise and eventually drown out the flow through the breach (ie up and downstream levels normalise). Temple and others (2005) noted that during this phase of development the eroding breach sides remained more or less vertical, consistent with observations from larger-scale tests under the IMPACT project (Vaskinn and others, 2004).

This stage relates to flow behaviour in the range T3- to T5 in Table 13, Appendix A.

Figure 9 - Image of breach expansion during reservoir drawdown
Photos courtesy of Greg Hanson, USDA-ARS Hydraulic Engineering Research Unit (HERU), Stillwater, OK, USA.

The main characteristic of a headcut failure is that the flow over the dam or levee creating the headcut does not change significantly while the headcut forms and cuts back into the bank. However, when the headcut erodes through the crest and into the upstream slope, the flow will then very rapidly increase leading to catastrophic failure (see Section 2.6).

2.3. Surface erosion

The different stages of surface erosion are shown below.

Stage 1 – Initial overflow and surface erosion

Erosion of the embankment surface by overflowing water. Most aggressive erosion on downstream face. Slow or no erosion of crest means that discharge across the crest of the embankment is not significantly affected. Flow concentrates erosion at discontinuities in the embankment surface.

This stage relates to flow behaviour in the range T1 to T2 in Table 13, Appendix A.

Figure 10 - Image of initial overflow and surface erosion

Stage 2 – Continued surface erosion, including crest erosion

Erosion of the downstream slope starts to cut into the embankment. Slower erosion of the crest starts to allow an increase in discharge, which in turn increases the rate of overall erosion. A mixture of surface and potential headcut formation can be seen in this photo.

This stage shows the transition of flow behaviour from T1 to T2 into T2 to T3 in Table 13, Appendix A.

Figure 11 - Image of continued surface erosion, including crest erosion

Stage 2 (continued) – Continued surface erosion, including crest erosion

The cycle of erosion of both the downstream slope and crest cuts deeper into the embankment, progressively allowing an increase in discharge. Rapid and widespread surface erosion removes material from the face of the downstream slope, and hence the eroding surface retreats upstream.

This stage relates to flow behaviour T2 to T3 in Table 13, Appendix A.

Figure 12 - Image of continued surface erosion, including crest erosion

Stage 3 – Continued surface erosion, including crest erosion and some breach widening

As erosion of the downstream slope and crest level becomes more aggressive, the control section for flow through the breach lowers and moves upstream (following the upstream slope). Some widening occurs, but erosion is still mainly vertical.

This stage relates to flow behaviour T3 to T5 in Table 13, Appendix A (although specifically T3 to T4 in this example).

Figure 13 - Image of continued surface erosion, including crest erosion and some breach widening

Stage 4 – Breach expansion during reservoir drawdown

Once the embankment section within the breach has eroded towards the bed, the width of the breach then grows. The rate and extent of growth is affected by the volume of reservoir water that can be released, and discharge through the breach eventually stops either through the release of all reservoir water, or because downstream flood levels rise and drown out the breach flow.

Figure 14 - Image of breach expansion during reservoir drawdown
Photos: EC IMPACT Project

The main characteristic of a surface erosion failure is that the flow over the dam or levee creating the erosion increases progressively as the erosion lowers the crest and erodes the downstream slope simultaneously (see Section 2.6).

2.4. Rockfill slump failure

The slumping of rockfill, or highly porous materials, is caused by high pressures of flow through the body of the dam or levee. Use of highly porous materials normally provides stability to a zoned structure or a structure with a core or watertight facing layer. High throughflows may arise from overflowing of the seal (core or upstream face) or fracturing of the seal. As the flow destabilises the porous material, slumps occur and material is washed out. The slumps progressively expose the watertight zone, core or upstream seal and eventually fracturing and failure occurs. When failure occurs the rate of release of water is rapid and catastrophic.

Figure 15 - Image of flow over thin protection layer leading to slumping or porous rockfill in rockfill erosion tests

Figure 16 - Image of flow over thin protection layer leading to slumping or porous rockfill and subsequent cracking and failure of protection layer in rockfill erosion tests
Photos: Miguel Ángel Toledo, Universidad Politécnica de Madrid

2.5. Internal erosion

While there are various mechanisms of internal erosion, the end result is a seepage path through or under the dam or levee, which may lead to internal erosion and progress through to full breach. The images below show the progression of internal erosion through the Teton Dam, ultimately leading to catastrophic failure (open breach).

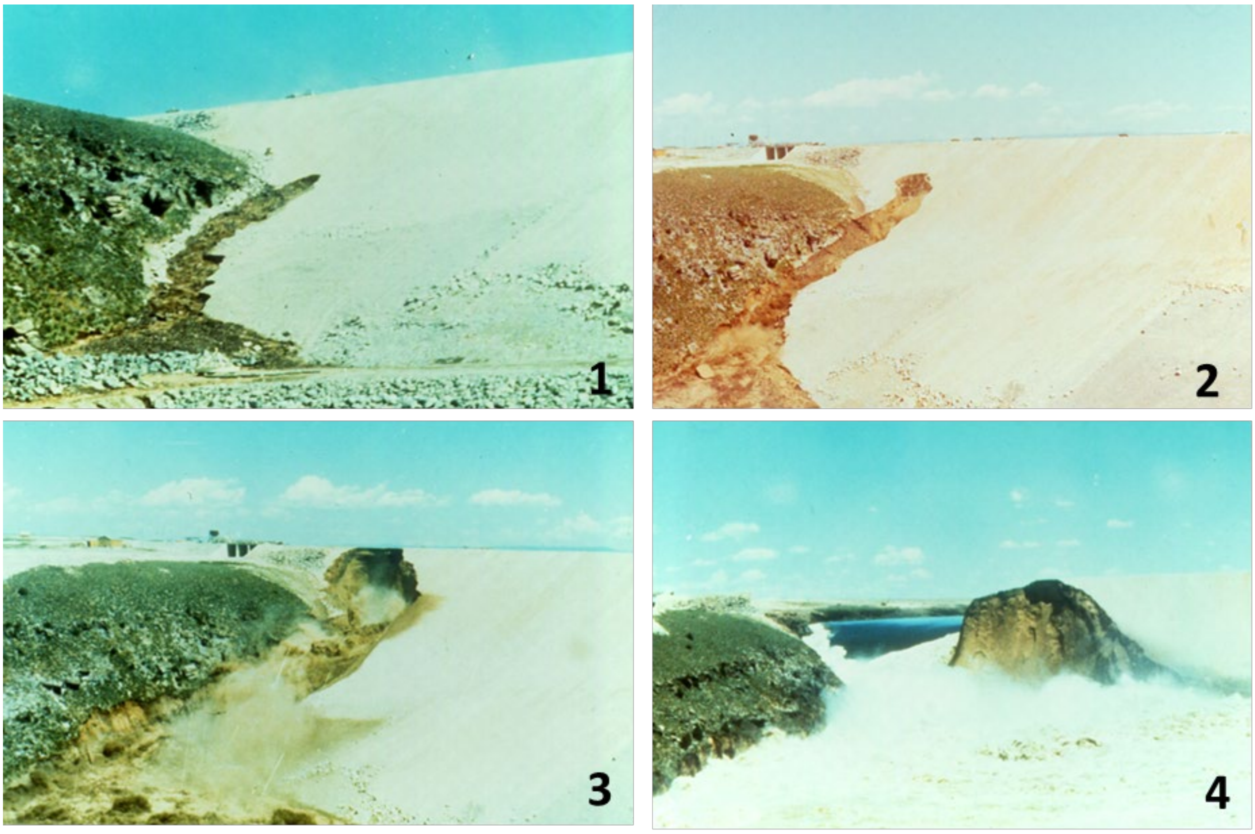


Figure 17 - Progression of internal erosion to open breach, through stages 1-4 (Teton Dam)
Photos: D Gillette, USBR

During the past 10 years a series of research efforts have resulted in a better understanding of the different internal erosion processes that can occur. The current state of knowledge is summarised in:.

- 2015 ICOLD Bulletin 164 (ICOLD, 2013)
- 2015(v4.0) USBR Best Practices in Dam and Levee Safety Risk Analysis (2019). Relevant chapters include:
    - III-1 Consequences of failure
    - IV-1 Erosion of soil and rock
    - IV-2 Flood overtopping failures of dams and levees
    - IV-4 Internal erosion risks for embankments and foundations
    - IV-1 was developed from the earlier ‘seepage and piping toolbox’
- 2011 to 2014 USBR Design Standard No. 13 Embankment dams
    - 21 chapters

The different physical processes that can occur are summarised below and in Figure 18. In particular, Figure 18 shows how the various combinations of material susceptibility, hydraulic load and soil stress condition are required for, and relate to, the different internal erosion mechanisms.

Summary of main mechanisms and descriptions of internal erosion (Source: USBR (2015), Table IV 4-1.)

- **Backward erosion piping (BEP)**

When soil erosion (particle detachment) begins at a seepage exit point and erodes backwards (upstream), supporting a ‘pipe’ or ‘roof’ along the way.

- **Internal migration (stoping)**

Occurs when the soil is not capable of sustaining a roof or pipe. Soil particles migrate downward primarily due to gravity, but may be aggravated by seepage or precipitation, and a temporary void grows in the vicinity of the initiation location until a roof can no longer be supported, at which time the void collapses. This mechanism may be repeated progressively until the core is breached or the downstream slope is over-steepened to the point of instability. Since, by definition, roof support is lacking, this mechanism typically leads to a void that may stope to the surface as a sinkhole.

- **Concentrated leak erosion/Contact erosion**

The US Bureau of Reclamation (USBR) merge these and classify as ‘scour’: Occurs when tractive seepage forces along a surface (ie a crack within the soil, adjacent to a wall or conduit, along the embankment–foundation contact) are sufficient to move soil particles into an unprotected area, or at the interface of a coarse and fine layer in the embankment or foundation. Once this begins, a process similar to backward erosion piping or internal migration could result. Scour does not necessarily imply a backward (upstream) development of an erosion pathway. Enlargement of an existing defect may occur anywhere along the seepage pathway.

- **Internal instability – suffusion and suffosion**

Both are internal erosion mechanisms that can occur with internally unstable soils. It is possible that these mechanisms as well as internal migration (stopping) can occur in complex glacial environments where tills, glacio-lacustrine and outwash deposit co-exist.

Suffusion involves selective erosion of finer particles from the matrix of coarser particles (that are in point-to-point contact) in such a manner that the finer particles are removed through the voids between the larger particles by seepage flow, leaving behind a soil skeleton formed by the coarser particles. With suffusion there is typically little or no volume change.

Suffosion is a similar process but results in volume change (voids leading to sinkholes) because the coarser particles are not in point-to-point contact.

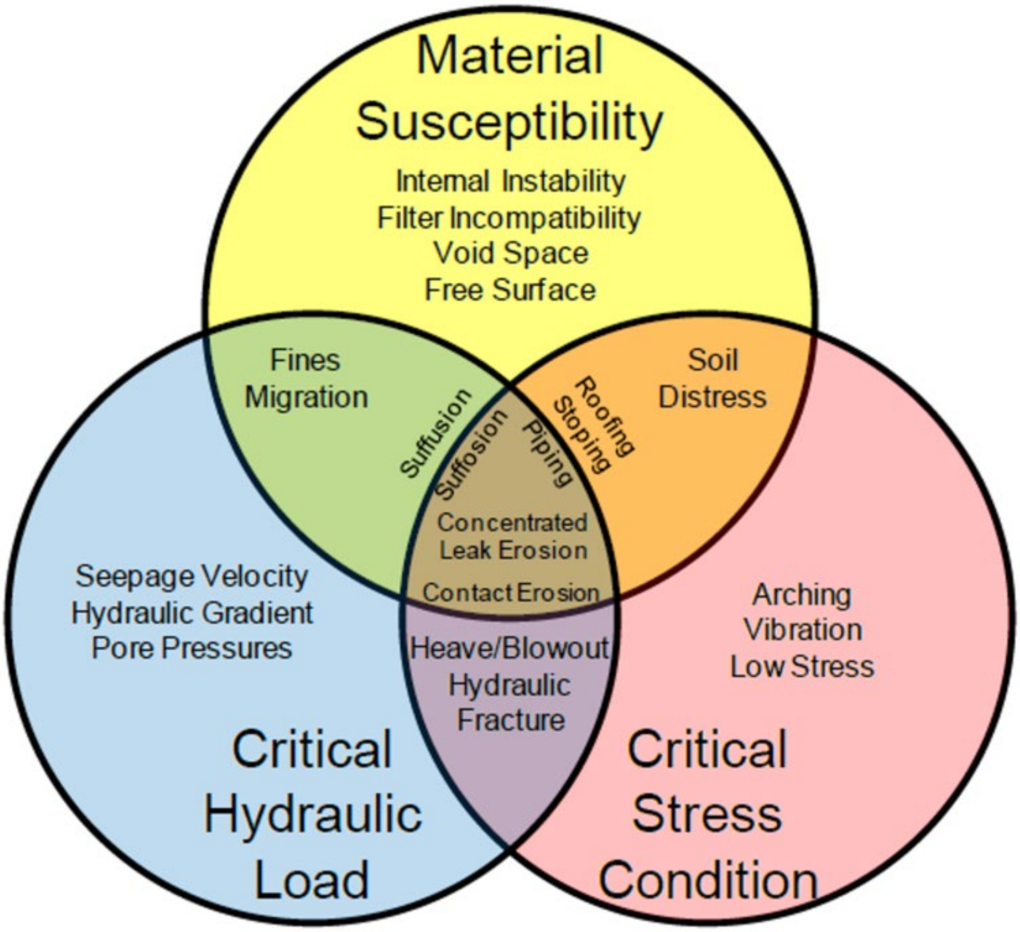


Figure 18 - Diagram showing the factors affecting the initiation of internal erosion
Source: USBR (2015), Figure IV-4-9.

While the understanding of internal erosion processes has advanced in recent years, this has not yet (as of 2019) transferred into industry tools for breach prediction. Current breach prediction models tend to require the user to assume an initial internal erosion flow path and size, rather than checking for and predicting erosion via the various potential processes.

2.6. Links between processes

The way in which breach progresses from initiation through to formation and widening can be via a variety of different processes. The process is very sensitive to changes in hydraulic load, soil erodibility and structure conditions and response. Figure 19 provides an event tree which shows some of the high-level processes (as described in Sections 2.1 to 2.5 above) and their potential interactions.

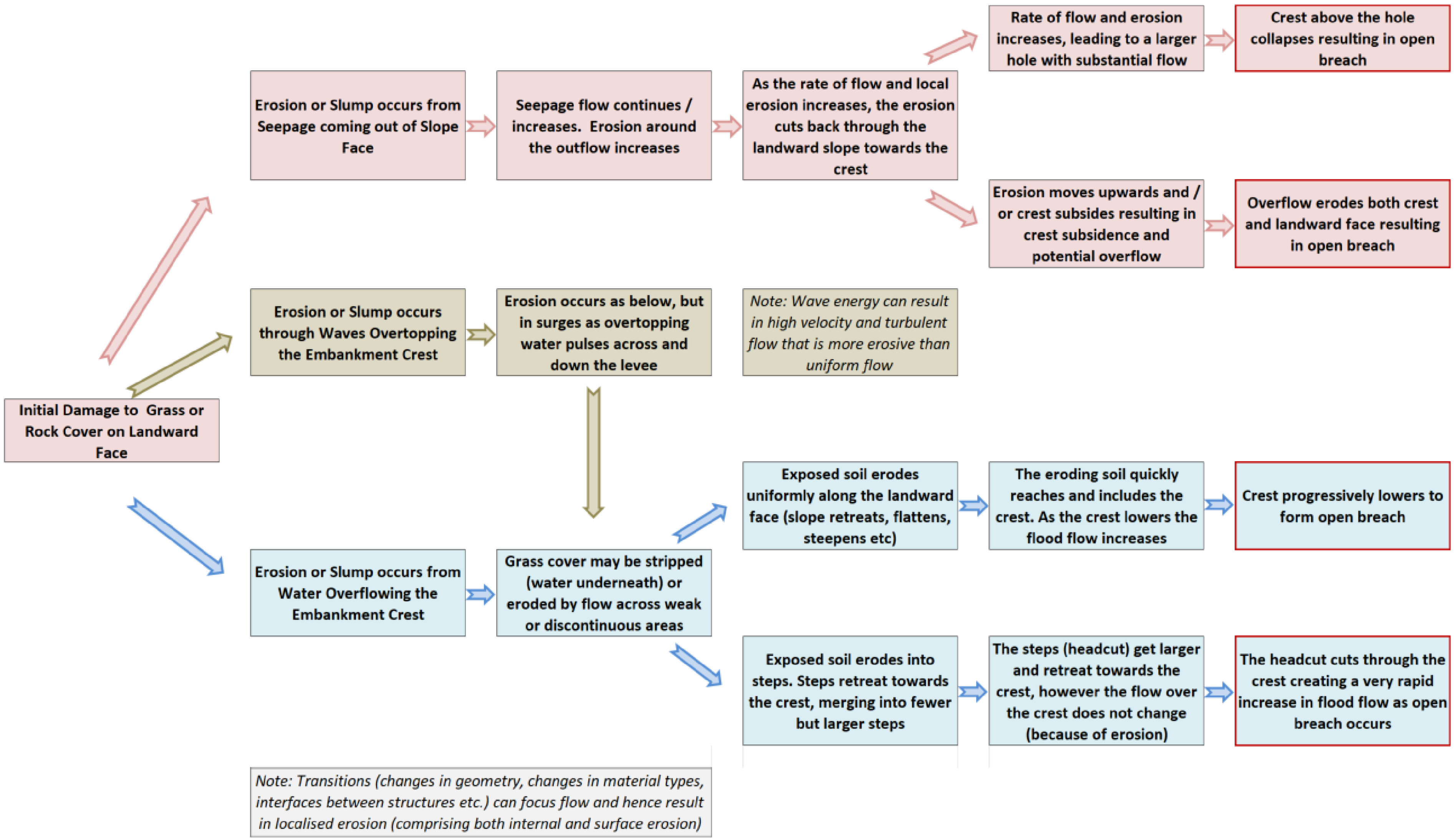


Figure 19 - Event tree showing potential sequence of and interlinkages between different breach stages and processes

2.7. The effect of different macro erosion processes on breach formation and the flood hydrograph

The different macro erosion processes (for example, headcut, surface erosion, slumping, internal erosion etc) affect the timing and rate at which breach formation and the release of floodwater occur. Ultimately, if left unchecked, each of these processes will result in catastrophic failure through open breach of the structure, but the path taken to reach this point varies.

Figure 20 shows a range of predicted breach hydrographs using different crest widths, soil erodibility and macro erosion processes. It is notable that the 3 plots showing slower and lower peak discharge result from headcut erosion, compared to surface erosion for each of the others.

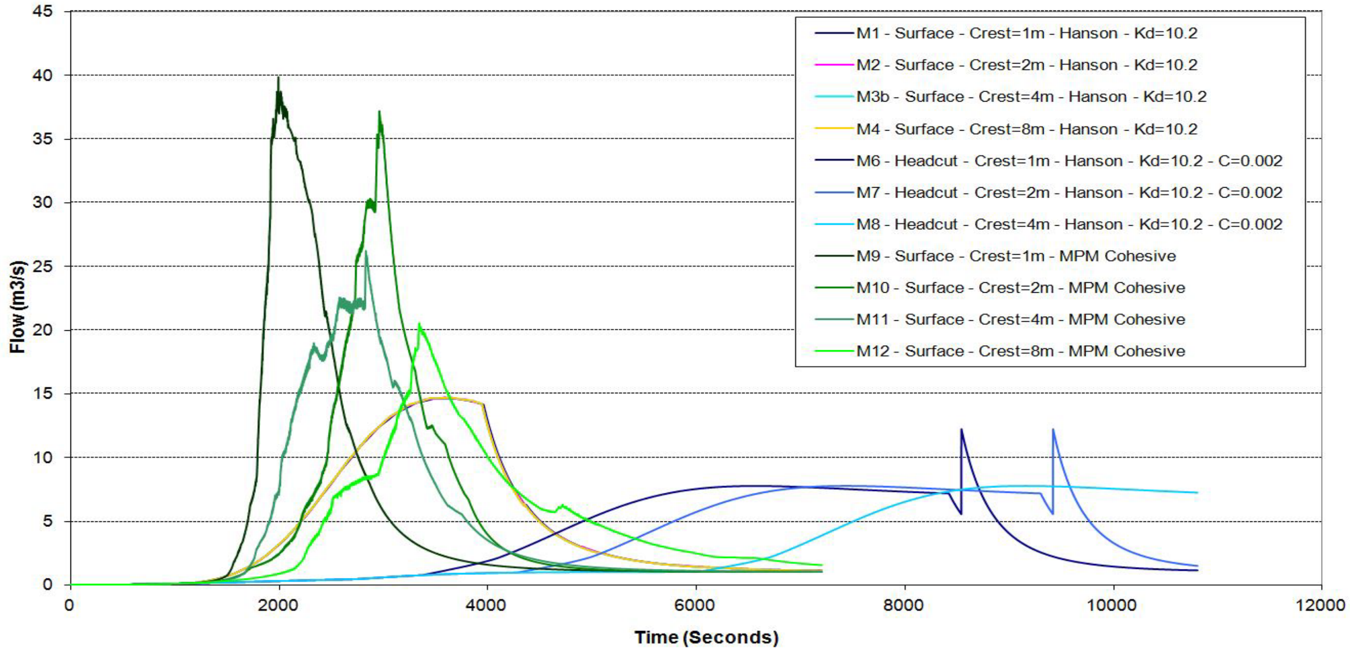


Figure 20 – Graph showing the effects of embankment geometry and erosion process – Outflow. Potential variation in flood hydrograph arising from different macro erosion processes

Notes: Run results to the left are from surface erosion simulations, to the right are from headcut simulations. If you want further info then also add 'Crest' represents levee crest width; 'Hanson' represents use of the excess stress erosion equation; 'MPM' represents use of the Meyer-Peter Müller sediment equation; 'K_d' is a measure of soil erodibility; 'C' represents rate of headcut retreat.

2.8. The effect of varying soil erodibility

Regardless of which erosion process occurs (headcut, surface, internal etc), a key parameter affecting the rate of erosion is the soil. Depending upon the type and state of the soil, the soil erodibility can vary by orders of magnitude, as shown in Figure 21. Correctly estimating or measuring the soil erodibility is therefore essential for a reliable estimate of erosion and breach behaviour.

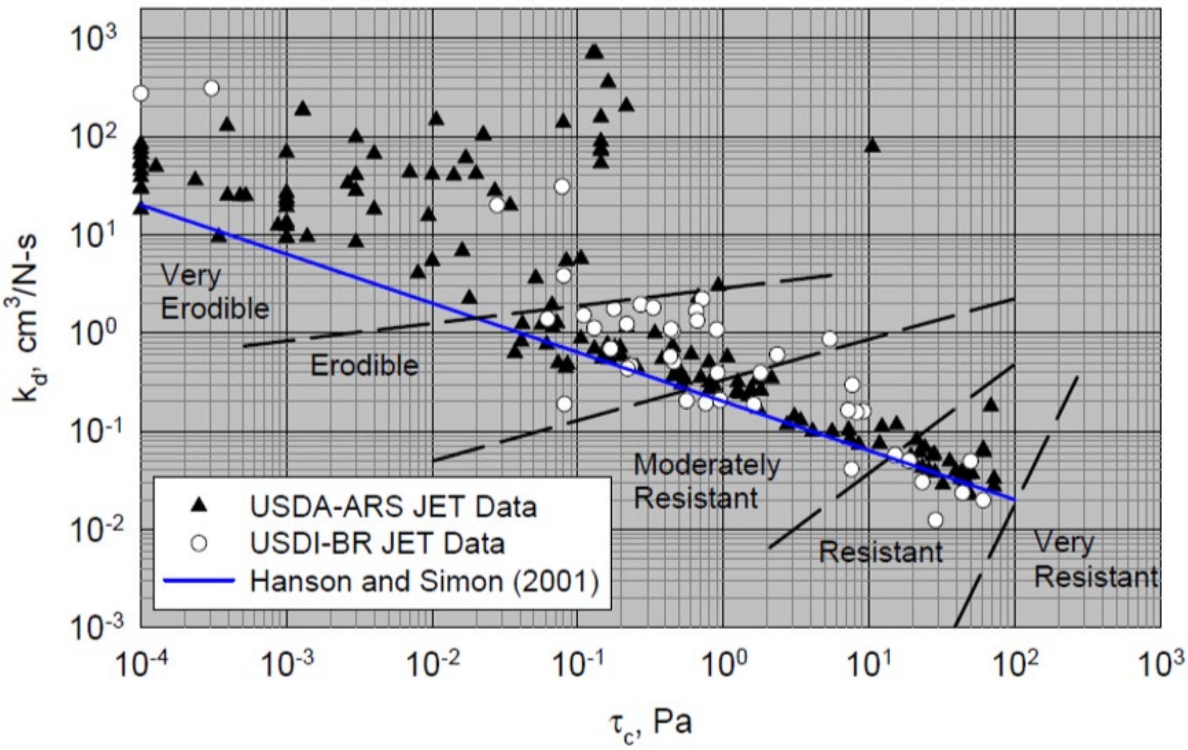


Figure 21 – Scatter graph showing the relationship between erodibility (Kd)and critical sheer stress (Tc) from JET tests on soil at the USDA-ARS Hydraulic Engineering Research Unit and USDI-BR Hydraulic Laboratory

Notes: cm^3/N-s = cubic centimetres per Newton-second; JET = jet erosion test; Pa = pascal; τ_c = critical sheer stress; USDI-BR = United States Department of the Interior Bureau of Reclamation.
Source: Hanson and others (2010).

Figure 22 shows how the nature of the flood hydrograph through the breach can vary. In this example, a levee with low erodibility (K_d=1) does not fail. However, with a K_d=10, failure occurs slowly, allowing the floodwater to drain slowly – hence a prolonged flood hydrograph with a relatively low peak discharge. With K_d=100 far quicker breach formation occurs, resulting in a more rapid, higher peaked flood hydrograph. With K_d=500, very rapid failure occurs with an associated rapid surge of floodwater. Note that the difference in K_d values shown here represent nearly 3 orders of magnitude.

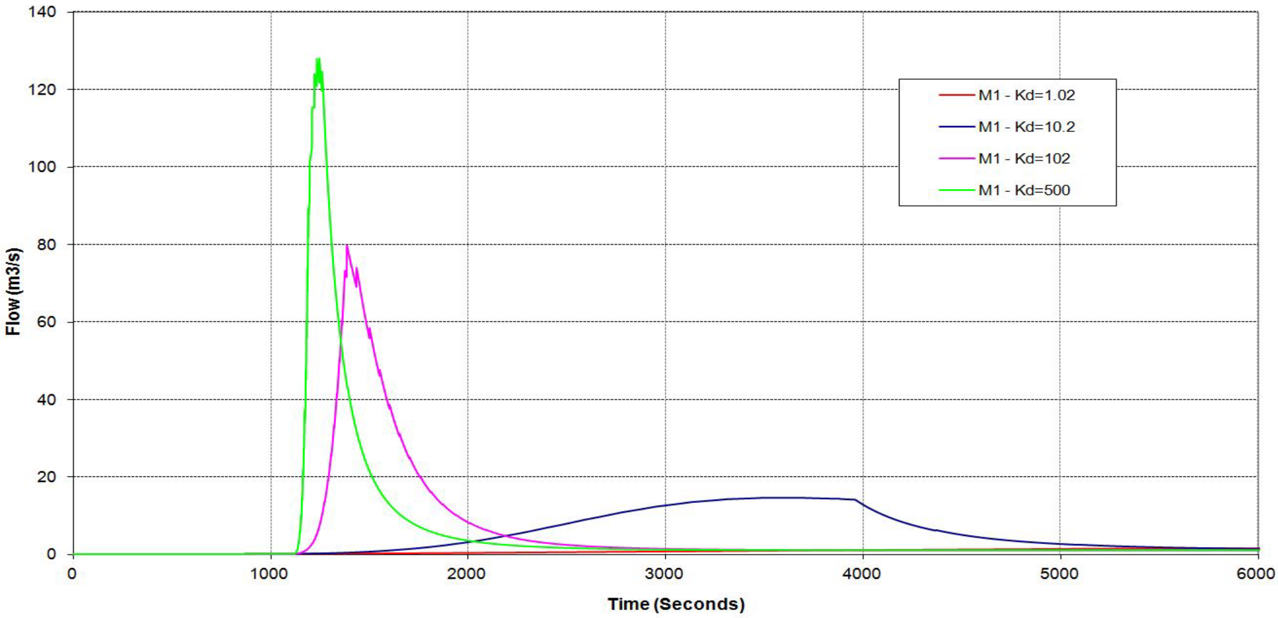


Figure 22 – Graph showing the potential effect of soil erodibility on breach flood hydrograph (outflow)

Effect of soil erodibility on size of drawdown capacity required to avert failure of dams

The Environment Agency 'Guide to drawdown capacity for reservoir safety and emergency planning' (Environment Agency, 2017) provides guidance on what is a recommended drawdown capacity for dams. Consideration 2 is the vulnerability to rapid dam failure, with the guide including guidance on alternative methods to determine the erosion index (Appendix C) and a tool for preliminary estimates of the time to failure (Appendix D, with worked example in Appendix E). Volume 2 includes a literature review and industry consultation on the range of likely time to failure for UK dams.

The practical conclusions were that for:

- highly erodible dams, the size of drawdown capacity required to avert failure is not physically practicable and instead dam safety should rely on structural measures to inhibit initiation of internal and external erosion
- resistant dams, the time to failure may be up to weeks, and installed drawdown capacity is a highly effective way of reducing the probability of dam failure in the event of a structural problem

2.9. Factors affecting macro erosion processes

While some levees and small dams may comprise simple, homogeneous structures, many are more complex. Complexities are introduced through the inclusion of different:

- geometries
- surface protection layers
- zones of different material types
- embedded structures

- variation in material state through the construction process (e.g. poorly compacted)

While each added complexity is designed to improve performance in some way, it also introduces transitions between uniform materials or geometry. Such transition boundaries typically introduce weaknesses by susceptibility to erosion; for example:

- changing surface geometry can focus external loads (flows and waves) to start erosion of and damage to the structure
- changing surface protection (roughness) can lead to turbulence and erosion around the end of protection layers
- embedded structures on the dam or levee (e.g. walls, steps) can focus overflowing water to erode around the structure
- embedded structures through the dam or levee can provide a preferential route for seepage and internal erosion

2.9.1. Erosion processes around surface protection and outfall

Figure 23 shows erosion occurring at multiple transition points, including:

- change between types of surface protection;
- around an outfall structure at the junction between the outfall structure and earth embankment
- at the interface between embankment and sheet pile walling

Figure 23 - Photo of erosion as a result of a transition
(Photo – MW Morris)

2.9.2. Internal erosion around pipes and services

Figure 24 shows the result of internal erosion occurring along the line of a pipe constructed through the dam. While seepage stops were included in the design, these were insufficient for the type of material and quality of construction.

Figure 24 - Photo of transitions as a focus for erosion
(Photo D Bowles/USBR/USACE)

2.9.3. Breach initiated by other processes

Breach can be initiated by other processes, with examples shown below.

- **Surface fissures due to desiccation:** Allow overflow and overtopping water to enter embankment body, raising pore pressure. Block formation can also affect erosion rates.

- **Mining subsidence:** Tensile stress leads to crack across embankment, in which concentrated erosion occurs when subject to differential head of water.

- **Animal burrows/ root systems:** Can provide preferential flow paths and increase hydraulic gradient for internal erosion.

- **Ruts in crest (animals, machines, bikes etc)**: Repeated use of crest can destroy surface protection layer and create low points in the crest, leading to focus points for overflow or overtopping.

- **Aircraft impact**: Reduces freeboard or causes direct breach.

- **Embankment instability**: Overburden loads combined with high pore pressures resulting in slips developing.

See 'Guide to risk assessment for reservoir safety management' (Environment Agency, 2013a, 2013b) Tables 8.8 and 8.14 for cross references to guidance for other combinations of threat and failure mode.

2.9.4. Surface protection measures

Surface protection measures, such as grass, rock or geotextiles, are often added to protect against and delay the onset of erosion (Figures 25 and 26). Since these measures affect the ability of the structure to withstand erosion damage, understanding their performance is also critical to reliably predicting breach. For a simple example of how grass protection might affect breach prediction, consider a levee needing to withstand a large storm flow that would overtop the levee by 0.1m for 2 hours or 6 hours. Grass cover may well limit erosion for a short time but could be compromised if exposed to prolonged overtopping – hence breach predictions using an appropriate measure of grass performance would give significantly different results for these 2 storms.

Figure 25 - Photo showing grass erosion: overflow at a depression in the crest initiating erosion at weak points in landward slope grass cover
Photos source: Environment Agency (2007).

Figure 26 - Photo showing grass erosion due to overtopping
Photos source: Environment Agency (2007).

The type and quality of grass cover also affects the soil state beneath. Grass root systems can strengthen soil against erosion and help maintain moisture levels. When soil becomes too dry, fissuring can occur (Figures 27 and 28) that can then affect the way in which failure occurs, by allowing water directly into the body of the levee.

Figure 27 - Photo showing embankment fissuring: Surface cracking in new embankment at Thorngumbald
Photos source: Dyer and others (2007).

Figure 28 - Photo showing embankment fissuring: depth of cracking in original embankment at Thorngumbald
Photos source: Dyer and others (2007).

2.9.5. Road crossings

Figures 29 and 30 below shows how erosion across an embankment with a protective surface – such as a road crossing – affects the nature of erosion. While the embankment material erodes easily, the road surface remains unaffected until subsidence due to the removal of material from beneath the surface results in failure. The protection offered by the road can be misleading. While the road surface could withstand a considerable depth of fast flowing water without any difficulty, the supporting bank material would rapidly erode after water depths exceed perhaps 200 millimetres. Removal of the bank material then undermines the road surface leading to collapse.

Figure 29 - Photo showing road cover affecting embankment erosion process

Photo courtesy of The Balance Small Business

Figure 30 - Photo showing overflow erosion at a small dam in Surrey in the December 2013 floods (Incident 388 in the EA database)
Photo courtesy of: Environment Agency

2.9.6. Walls and barriers

Hurricane Katrina highlighted the effects of overflow on wall structures on levees, with some designs being susceptible to toe erosion and subsequent collapse. Such erosion processes and the susceptibility of the structure to erosion and failure are very design/site specific (Figures 31 and 32).

Figure 31 – Diagram showing overflow damage to concrete flood walls during Hurricane Katrina.

Figure 32 - Photo showing overflow damage to concrete flood walls during Hurricane Katrina
Photos: USGS https://soundwaves.usgs.gov/2006/01/

2.9.7. Zoned dams and levees

Zoned dams and levees constructed from different types and hence erodibility of material can erode through to catastrophic failure in different ways. Combinations of headcut and surface erosion may occur, resulting in flood hydrographs that can differ significantly from each other. Some layers may erode preferentially, while others may resist erosion. The difference between flood hydrographs from different zoned structures can be large – both in terms of the timing and the magnitude of peak outflow (Morris and Hassan, 2018).

The graphics below show the breach erosion process (Figure 33) and outflow hydrograph results (Figure 34) for an example structure comprised of 2 layers of material with different erodibility. In each case, the structure size and the reservoir volume retained are the same.

Figure 33 shows how the erosion process evolves when the structure comprises 2 layers of soil with different erodibility. The upper 3 images show erosion with a more erodible upper layer, while the lower 3 images show the situation reversed. The animations were generated by the HR BREACH/EMBREA breach model.

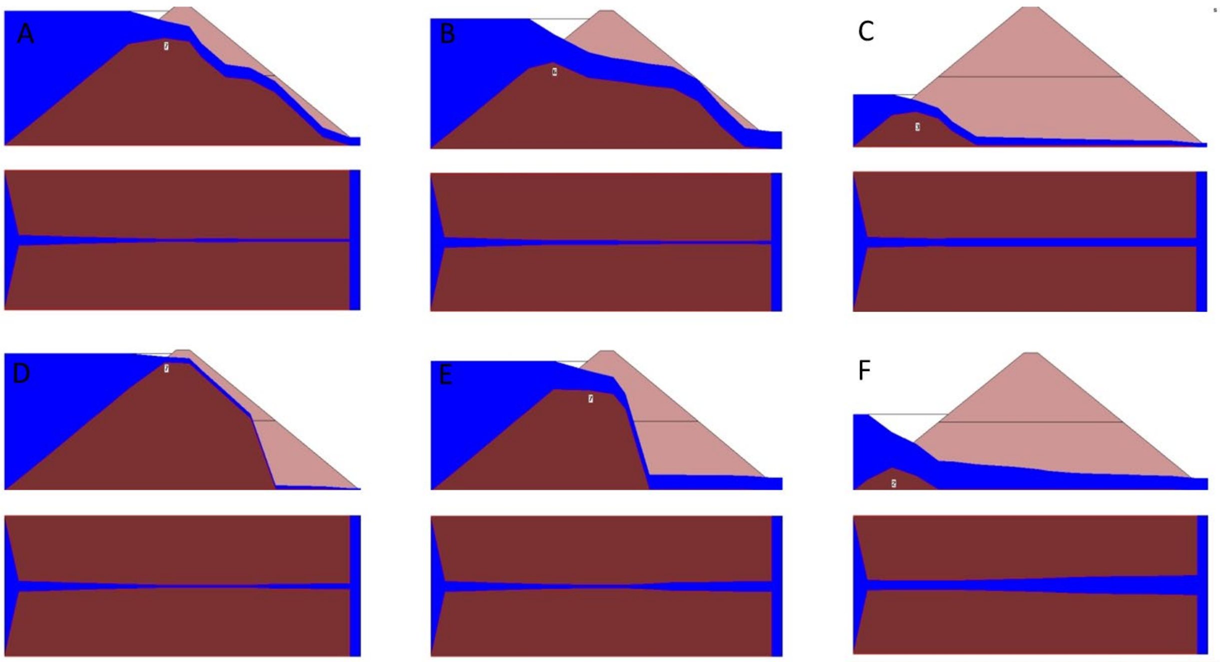


Figure 33 – Different erosion behaviour with layers of material of different erodibility

Figure 34 shows how the effect of different layer erodibility affects the predicted outflow hydrograph. The 2 blue plots (M1-Homo…) show results for a homogeneous structure constructed from 2 different soil types. Structure one erodes rapidly, resulting in a quick, high peak flood hydrograph; the other structure erodes slowly such that the reservoir drains as the crest invert erodes, resulting in a prolonged, low peak release of floodwater.

The pink and yellow plots (M1-Type1 - 2 layer…) show results for a zoned structure comprising 2 layers of equal thickness but different erodibility. These plots start to follow the homogeneous structure behaviour for one of the types of soil erodibility, and then tend towards the other once the layer of soil has been eroded. The orange and brown plots show similar characteristics, albeit for 2 layers with unequal thickness. Figure 34 demonstrates just how significant the effect of different zones of soil erodibility can be for breach prediction. Res2500 indicates the size of the reservoir.

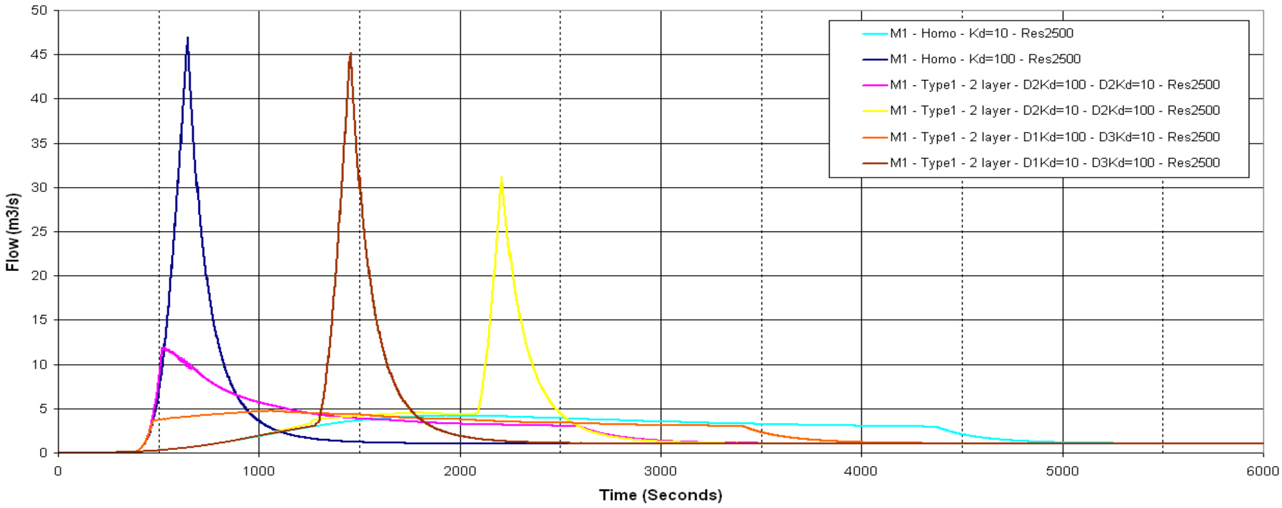


Figure 34 - Graph - indicative plot showing different timing and characteristics of breach flow affected by embankment zoning (breach outflow)

2.10. The effect of varying hydraulic load conditions

Varying the hydraulic load condition will significantly affect how the breaching process develops. Under a simple overflow condition, steadily increasing the amount of water over the crest of the dam or levee increases the shear stress on the exposed surfaces and eventually a critical shear stress will be reached where soil erosion will start to occur. After this point, the duration and magnitude of the eroding flow will dictate the extent of damage (erosion) that will occur. The rate of breach progression through breach initiation, formation and growth will depend upon the type of hydraulic load (brief storm; long-duration flood; rapidly varying levels etc).

Specific types of hydraulic loading have a big effect on the breaching process. These are summarised below.

2.10.1. Waves

Waves can damage dams and levees through both impact damage / erosion and through overtopping flows. As waves crash upon a levee, the dissipation of the waves' energy can initiate dam and levee erosion. Empirical equations are available to estimate how grass and rock cover might perform under such conditions.

Coastal levee breach due to wave overtopping

Figure 35 - Photo of waves impacting exposed face of a coastal levee

Figure 36 - Photo of waves overtopping across landward face of a coastal levee

Figure 37 - Photo of erosion of landward face of a coastal levee

Figure 38 - Photo of slumping and collapse of landward face of a coastal levee

Figure 39 - Photo of open breach of a coastal levee
Photos: Storm, 22 December 1954, Germany - Andreas Kortenhaus, University of Ghent

2.10.2. Tides

A breach through tidal assets means that hydraulic loading varies according to the tidal cycle, which in turn can also be affected by wind and surge effects. The tidal cycle may offer the chance to intervene and repair or protect the structure against further damage. However, a tidal location also means a potentially unlimited source of floodwater.

2.10.3. Canals

Canals have a narrow range of breach formations because of their geometry. Canals are often perched on hillsides and have discrete ponds which will drain if a breach occurs. When a breach occurs, and water starts to drain from the canal pond, soil erosion cuts back into the bed of the canal. Since water flows to the breach from both directions along the canal pond, erosion tends to cut back along the canal bed in each direction. When this occurs, the control of water flow out of the canal changes from the breach to a form of weir flow within the canal (in each direction). As such, the rate of breach growth is first controlled by the breach initiation process (see Sections 2.2 and 2.3) and eventually by the geometry of the canal pond.

Figure 40 - Image of Middlewich Canal breach, March 2018
Photos: Vision Aerial (working for CRT)

2.10.4. Reservoir size and shape versus erodibility

The size and shape of a reservoir (or indeed, the nature of any hydraulic load) in relation to the erodibility of the dam or levee material, dictate the rate of floodwater release and hence the characteristics or shape of any flood hydrograph.

Where a reservoir has a relatively small surface area, and the dam or levee is constructed from an erosion-resistant material, the reservoir level may drop at much the same rate as the invert level of the breach erodes. This creates a slow flood flow, since the discharge through the breach remains relatively low as the slow erosion process allows progressive draining of the reservoir.

The opposite occurs where a reservoir has a large surface area and the dam or levee is constructed from an erodible material. Erosion of the breach is rapid, leading to a situation where the reservoir cannot drain down at the same rate as the breach invert erodes. This results in a very rapid increase in breach flow.

Figure 41 shows 3 different breach hydrographs arising from erosion prediction for the same reservoir area, but using erodibility (K_d) values of 25, 50 and 100. The shape of the breach outflow hydrograph changes as the K_d value reduces relative to the reservoir area. In this example, a K_d value of 100 allows rapid erosion of the breach invert, and hence a rapid rise and fall in the flood hydrograph. As the value of K_d is changed to 50 and then 25, the rate of breach invert erosion reduces and the time for breach formation extends. The nature of the outflow hydrograph changes to show a slower, drawn out release of water, with a significantly lower peak discharge value.

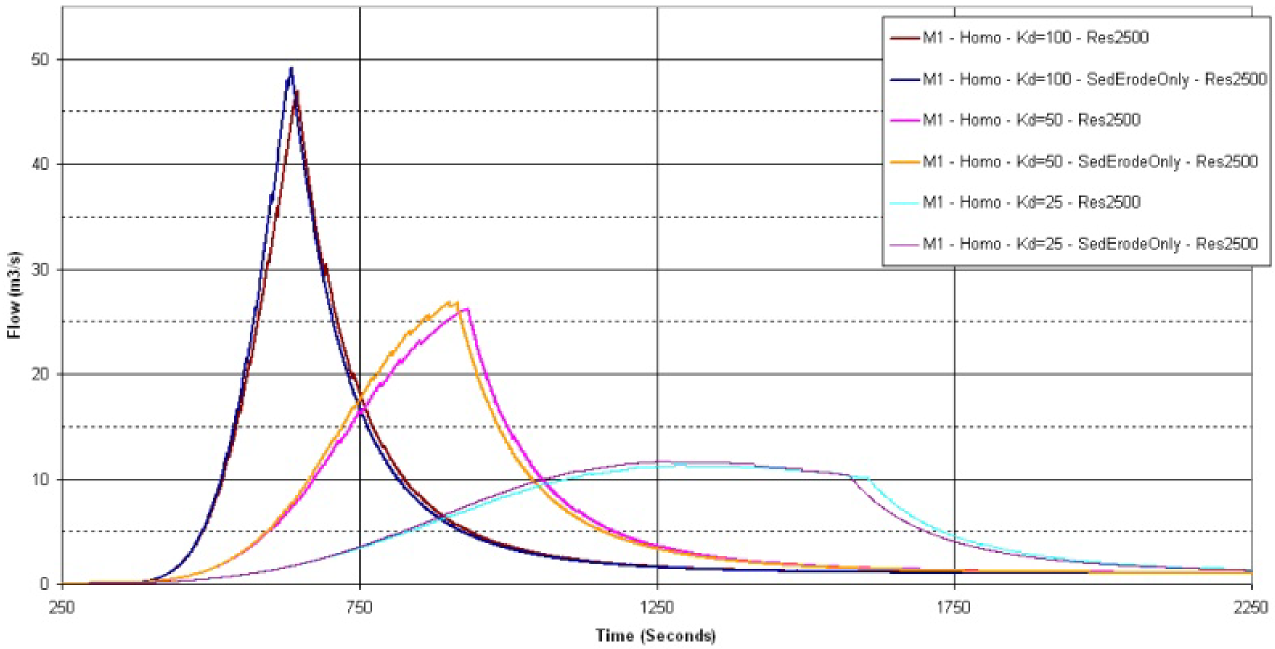


Figure 41 - Graph showing examples of different breach hydrographs arising from varying soil erodibility compared to a fixed reservoir surface area (breach outflow)
Note: The change in breach characteristic as the soil erodibility is changed (K_d of 100, 50 or 25 for a given reservoir size). The two curves shown for each K_d scenario reflect different ways of modelling the detailed erosion process - the magnitude of any difference is small in comparison to the effect of changing soil erodibility.

2.10.5. Flow system modelling

Where breach, or multiple breaches, form part of a flow system model, then the breach prediction process can affect conditions throughout the model. To avoid imposing conditions on the system model, the breach prediction process should be fully integrated within the flow model such that the simulation is allowed to predict where, when and how various breaches may occur. The specific timing and nature of the predicted breach processes will then affect how flood flows progress through the simulation.

2.11. Summary

This chapter has described the 4 main breach processes and how the processes are often linked. The sensitivity of peak flow and timing to erodibility and erosion processes was shown in:

- Figures 20 and 21, where the magnitude of peak flow varies by a factor of over ten
- Figures 35-39, which show variation in flow by a further factor of ten where embankments are zoned
- Figure 41, which shows peak flow varying by a factor of 5 depending on reservoir surface area

This review of physical processes confirms the wide range of peak breach flows and time to failure that can occur, and thus the importance of a good understanding of physical processes. This is relevant to all user types.

3. Dam and levee breach prediction methods

This chapter introduces the different methods that are currently available for predicting breach. It explains how they differ in their data requirements and relative accuracy of breach prediction.

3.1. Different approaches for predicting breach

Approaches to predicting breach can be divided into 4 groups:

1. rule of thumb/estimation using available historical evidence
2. parametric models
3. semi-physically based models
4. physically based models

Subsequent subsections describe these groups of approaches. For more detail:

- Table 3 provides a summary of different methods and modelling approaches, including an indication of their relative accuracy, limitations and applicability
- Table 4 provides an overview of the different relationships or assumptions typically used to predict breach processes within the different types of prediction method listed earlier in Table 3.

With any of these approaches, the reliability of the results will depend upon (i) the reliability of the data used, combined with (ii) the inherent uncertainty within the prediction approach adopted.

Data requirements

It is implicit that any breach analysis requires as an absolute minimum reliable information on the surface geometry of the embankment. For semi-physically based models and physical process models (Groups 3 and 4), it is also necessary to have information on the internal composition of the embankment, and properties of both the embankment and its foundation.

It is accepted that in many situations such information is not available and would have to be obtained by ground investigation. In such situations, options for obtaining data (in addition to ground investigation) include preliminary analysis using parametric models or carrying out more detailed models using credible ranges of soil parameters. For example, desk studies of likely sources of fill and construction methods in use at the date of construction of the embankment can provide useful information.

For new embankments the designer can use breach analysis to assist in specifying the embankment geometry, internal composition and materials.

The level of analysis will depend on:

- the use to which the results will be put
- the data available on the composition and construction of the embankment at risk of breach
- the uncertainty that is acceptable
- the resources available/cost of improving accuracy

Current methods available for scoping failure due to breach and using this to decide on what level of analysis is appropriate are:

- Stage 1 of RARS (Environment Agency, 2013a, 2013b)
- Guidance on risk management from the USACE/USBR – in particular Chapter I-3 on 'Potential failure mode analysis' (USBR, 2015)

3.1.1. Rule of thumb/estimation using available historical evidence

Methods for generating simple estimates of breach vary from assuming a breach of a certain size has instantly formed, to assuming a breach based upon a factor of the levee or dam height, to assuming a breach similar to failures that have previously occurred. The methods used often relate to the users needs, for instance incident response often consider a different approach than spatial planning.

The simple assumption of an instantaneous breach width allows for flood risk calculations to be made and the nature of potential flooding to be investigated, but offers little certainty regarding the breach prediction. Such assumptions will likely introduce large errors into any flood risk calculation, but are used to provide a reasonable worst case scenario to work with.

Using the dam or levee height to predict a potential breach width is better than guesswork, but still highly uncertain since it takes no account of the physical processes that will occur.

Using historical data as a guide to the potential breach size is far better than simply guessing, since the historical breach is likely to reflect the size of a flood and type of erosion that could occur within that catchment. However, the previous breaches will be event- and location-specific and may not necessarily reflect conditions that might occur at the actual location.

An alternative simple estimation approach (for dambreak) is directly estimate the potential depth of water downstream after dam failure. An example of such an approach is that the depth of flooding downstream is half the height of the dam, This simplification is the basis of the screening method given in Appendix 1 of ANCOLD guidelines to risk assessment (ANCOLD, 2003) and Tier 1 analyses for the 'Guide to risk assessment for reservoir safety management' (Environment Agency, 2013a, 2013b).

- **Indicative effort**: Minimal – based upon simple assumptions/data
- **Data required:** Minimal - simple assumptions and/or historical data
- **Indicative outputs:** Limited to simple estimation of final breach size/flood depth

3.1.2. Parametric models

Parametric models, such as Froehlich (2016a, 2016b) and Xu and Zhang (2009), allow breach geometry, formation time and peak outflow to be estimated through the regression analysis of historical dam failure data. These have advantages in their ease and speed of use, but can have great uncertainty in their application and are therefore not typically suitable for high-risk applications, where uncertainties can have a large impact.

Parametric models are typically based upon historical dam failures rather than levee failures, and hence their applicability to levee breach is in question.

- **Indicative effort:** 1–2 hours (mainly to collate and cross-check the approximate data to be used)
- **Data required:** Limited – typically reservoir volume, dam type and height and (for Xu and Zhang [2009]) erodibility category (high/medium/low)
- **Indicative outputs:** Most commonly peak discharge; some equations also time to peak and breach width; does not provide shape of flood hydrograph

3.1.3. Semi-physically based models

Semi-physically based models take breach geometry and formation time, or soil erosion rates, as input values to produce a breach hydrograph. No physical erosion processes are modelled; rather the flow of water through the user-defined breach is calculated using simple fluid dynamic equations, such as weir and orifice flow. These provide no improvement in the accuracy of predicting a breach over parametric models, but improve on the process of converting the assumed breach results into outflow hydrographs:

- **Indicative effort**: 1–2 hours (checking data etc); methods are typically embedded within flow modelling software; hence time is spent defining the breach 'module' within overall flow modelling approach
- **Data required:** Limited – but important; user-defined values are required for the rate of erosion, rate of breach growth and nature of breach growth, and this requires careful judgement and/or historical data
- **Indicative outputs:** Prediction of flood hydrograph through breach

3.1.4. Physically based models

There are several physically based process models, such as EMBREA, DL Breach and WinDAM available for engineering application. They consider the complex geotechnical, structural and hydraulic behaviour of an embankment dam and its impounded reservoir. While generally more time-consuming than parametric and semi-physical models, physical process models tend to provide results with a greater certainty and accuracy. They are more suitable for higher-risk breach scenarios, where accuracy and reliability are critical in providing results within the acceptable bounds of uncertainty.

- **Indicative effort:** Varies according to the type of the physical process model:
    - about 4 hours to set up simple 1D-2D model; once established, different breach scenarios can be modelled with minimal further effort

  - a few days for more complex 3D models
  - Using more complex models allows more detailed analyses to be performed – including Monte Carlo simulations; this allows a more detailed understanding of breach to be achieved, but naturally takes longer for analysis of the data
- **Data required:** Soil parameters, structure design and geometry and time-varying hydraulic loading; key parameter will be soil erodibility
- **Indicative outputs:** Prediction of the breach formation process leading to breach geometry and detailed flood hydrograph

As computing power increases year on year, the option of analysing breach processes in even more detail is also becoming a reality through the use of integrated seepage, flow and erosion computational fluid dynamics (CFD) models in 3D. These can reduce some of the uncertainties in the breach prediction process still further – for example by providing a more rigorous calculation of flow and erosion conditions. Significant uncertainties, however, still lie in understanding and representing the soil structure and its erodibility at both macro and micro scales. This is the focus of current research initiatives.

Table 3: Examples of different erosion and breach prediction methods

Prediction method	Level of damage predicted	Data used/required	Relative accuracy[1]	Comments
Grass, rock and revetment cover				
CIRIA 116 (Hewlett and others, 1987)	Performance of cover material to point of failure	Design curves based upon earlier field trials with added factor of safety User only need define grass cover condition	Various	Published in 1987 based upon earlier field and lab data Limited range application Contains built-in factors of safety. No consideration of underlying soil type
River and channel revetments: a design guide (Escarameia, 1998)	Performance of cover material to point of failure	Various calculation methods detailed	Various	Published in 1998 arising from Environment Agency project W5-029. Guidance on solutions and methods to calculate designs
The Rock Manual. The use of rock in hydraulic engineering (2nd edition) (CIRIA, 2007)	Performance of cover material to point of failure	Various calculation methods detailed	Various	

[1] Very poor ±500%; Poor ±250%; Fair ±100%; Good ±50%; Very Good ±25%.

Prediction method	Level of damage predicted	Data used/required	Relative accuracy[1]	Comments
International Levee Handbook (CIRIA 2013)	Performance of levee to point of failure via specific processes	Various calculation methods detailed	Various	Published in 2013 Covers all aspects of design and management of levees, including methods for analysis of specific processes
Initiation of internal erosion				
Seepage and piping toolbox (Fell and others, 2008a,b)	Tool for use to assess annual likelihood of dam failure and release of contained water due to internal erosion	Various calculation methods detailed, based on historical failure rates	Various, considered by some to be unreliable, as assessment too subjective	Now replaced by below
Reclamation "Best practices and risk methodology", Chapter IV-4 Internal erosion risks for embankments and foundations Periodic updates (2010 onwards, latest version on website [USBR, 2015])	As above	Various calculation methods detailed	Dependent on experience of user and data available	Reclamation stress that "*should not be used as a stand-alone reference. In many cases, additional details should be sought from the available references or an experienced risk analyst*"

Prediction method	Level of damage predicted	Data used/required	Relative accuracy[1]	Comments
ICOLD Bulletin 164 (ICOLD, 2013)	Conditions for internal erosion to occur	Various calculation methods detailed	Various	Use to determine likelihood of internal erosion occurring
Simple breach estimation				
Assumed breach width	Assumes complete failure	Based on historical events	Very Poor (Perhaps 'Poor' if prediction is for same magnitude of historical event and same failure mechanism)	Only applicable for same catchment, similar location, similar levee design and materials
Time and width linked to height (Brunner, 2014)	Assumes complete failure	User defines relationships within HEC-RAS (Hydrologic Engineering Centre-River Analysis System) model	Very Poor (Perhaps 'Poor' if prediction is for same magnitude of historical event and same failure mechanism)	Applicable for same catchment, similar conditions.

Prediction method	Level of damage predicted	Data used/required	Relative accuracy[1]	Comments
Empirical breach models				
Regression equations (See West and others [2018] and Morris [2011] for summaries) Also see Wahl (2004) for assessment of uncertainty and performance	Assumes complete failure	Simple use of reservoir volume, dam height and occasionally additional information	Poor	Typically, simple equations developed by fitting relationships to historical dam failure data
Xu and Zhang (2009) *(Table 4, Method 2)* (For performance evaluation, see Wahl, 2014)	Assumes complete failure	Simple reservoir and dam parameters (volume, height) plus indicative erodibility of soil (high, medium, low)	Poor (but better than equations not using measure of erodibility) Accuracy will depend upon how similar study dam is in comparison to failure data set used to develop the equations	Suitable for quick estimation of potential breach conditions Unique for peak discharge equations; these allow the user to define high, med or low soil erodibility
Froehlich (1995, 2016b) *(Table 4, Method 2)*	Assumes complete failure	Simple reservoir and dam parameters	Poor Accuracy will depend upon how similar study dam is in comparison to failure data set used to develop the equations	

Prediction method	**Level of damage predicted**	**Data used/required**	**Relative accuracy[1]**	**Comments**
Semi-physically based breach models (User entered data – user defines breach geometry)				
HEC-RAS (Brunner, 2014) *(Table 4, Method 3)*	Breach flow as breach opening grows to defined geometry	Simplified physical – user defines flow velocity–erosion relationship	Variable accuracy: can be misleading since results depend upon the user-defined set-up	For use in river system modelling.
Many other flow models also offer this type of functionality				
Physical process models				
Engineering tools				
AREBA (a rapid embankment breach assessment) *(Table 4, Method 4)* (Van Damme and others, 2012)	Predicts breach failure (breach dimensions, breach flood hydrograph) from defined initial conditions Fast, simplified prediction of breach failure through internal erosion and overflow via headcut or surface erosion	Dam and reservoir geometry, hydraulic boundary conditions, soil parameters – in particular soil erodibility (K_d)	Fair Model based upon the performance of HR BREACH, but simplified processes to provide a high-speed model suitable for use in system risk modelling	
For more information see: https://web.sbe.hw.ac.uk/frmrc/downloads/FRMRC2_WP4_4_UserReport.pdf				

Prediction method	Level of damage predicted	Data used/required	Relative accuracy[1]	Comments
DL Breach *(Table 4, Method 4)* (Wu, 2013, 2016)	Predicts breach failure (breach dimensions, breach flood hydrograph) from defined initial conditions	Dam and reservoir geometry, hydraulic boundary conditions, soil parameters – in particular soil erodibility (K_d)	Good	
For more information see: https://adweb.clarkson.edu/~wwu/DLBreach.html				
HR BREACH *(Table 4, Method 4)* [Mohamed, 2002]	Predicts breach failure (breach dimensions, breach flood hydrograph) from defined initial conditions Predicts breach formation via internal erosion, headcut and surface erosion processes; includes performance of grass and rock cover layers and the failure of composite (core) structures	Dam geometry and reservoir bathymetry, hydraulic boundary conditions, soil parameters – in particular soil erodibility (K_d)	Good Model validated through the Dam Safety Interest Group Breach Modelling project (Ref USBR report)	

Prediction method	Level of damage predicted	Data used/required	Relative accuracy[1]	Comments
For more information see: www.dambreach.org				
EMBREA *(Table 4, Method 4)* (Morris, 2011)	Predicts breach failure as with HR BREACH, but includes breach processes through zoned dam and levee structures	Dam geometry and reservoir bathymetry, hydraulic boundary conditions, soil parameters – in particular soil erodibility (K_d)	Good	EMBREA evolved from HR BREACH; hence contains the same functionality plus the additional option of breach through zoned structures
For more information see: www.dambreach.org				

Prediction method	Level of damage predicted	Data used/required	Relative accuracy[1]	Comments
WinDAM C *(Table 4, Method 4)*	Predicts breach failure (breach dimensions, breach flood hydrograph) from defined initial conditions Surface erosion prediction via headcut process only; includes internal erosion breach prediction; includes simulation of inflow, upstream reservoir, grass cover and breach to provide a prediction of breach growth in time and the outflow flood hydrograph	Dam geometry and reservoir bathymetry, hydraulic boundary conditions, soil parameters – in particular soil erodibility (K_d)	Good – validated model using high-quality test data from 1–2 m high levee breach tests for predicting headcut breach process	Model only predicts headcut; misses surface erosion processes This is the original validated headcut model from USDA-ARS HERU Other models simulating headcut tend to copy this model
For more information see: http://go.usa.gov/cupCF				

Prediction method	Level of damage predicted	Data used/required	Relative accuracy[1]	Comments
			It should be noted that the best accuracy listed is 'Good'. This reflects the fact that there remains considerable uncertainty within the processes that breach models predict	
Research tools				
As computational flow modelling software advances, simulation of flow in 3D becomes more commonplace. Numerous commercial codes are available for doing this. These codes are increasingly extended to include sediment erosion and to also link with other models – such as internal seepage and breach processes (block failure, removal etc). Currently, these models require considerable effort and specialist expertise to create for the simulation of real breach formation processes (i.e. not simply flow with sediment transport). It is likely that as models become more user-friendly and commercialised, breach prediction models will progress from the industry tools listed above, which are mainly 1D/2D models, towards more fully integrated 3D models, simulating flow, erosion, internal seepage and structure stability/block failures simultaneously. Examples of research development in this area are (i) use of the Basement model to simulate breach formation (including seepage and block failure) as well as the subsequent flood propagation (for more information see www.basement.ethz.ch/) and (ii) development of the Kratos model (Larese and others, 2018).				

Table 4: Relationships or assumptions typically used in the different erosion and breach prediction methods

Level of analysis/type of model or method	Physical processes: Initiation	Continued damage	Breach formation	Breach widening
(1) Rule of thumb/ historical evidence	N/A	N/A	N/A	N/A
	Final breach dimension predicted on basis of historical size or estimated by a multiple of levee height			
(2) Parametric models	N/A	N/A	N/A	N/A
	None of the individual processes are predicted Final breach peak discharge and sometimes timing and breach geometry are predicted by equations created from regression analysis of historical dam failures. The regression analyses tend to group failures together, so ignoring the factors affecting each specific failure			
(3) Semi-physically based models	N/A	N/A	User defined rates of erosion, or erosion relationships (eg erosion rate linked to flow velocity) are used to allow flow models to 'grow' a breach according to time or water datums	
(4) Physically based models: Headcut erosion (cohesive, erosion-resistant soils):	Uses grass performance/ rock stability relationships to determine when the cover layer would fail; once conditions exceed the performance curve, instantaneous failure of the cover across the whole structure is assumed	Uses USDA SIMBA/WinDAM headcut model This uses the linear excess stress equation, requiring the user to define soil erodibility and the soil critical shear stress (initiation of erosion) Predefined process of erosion down and back through levee until breakthrough Lateral widening rate based upon a multiple of breach bed erosion rate		

<table>
<tr><th>Level of analysis/type of model or method</th><th>Physical processes: Initiation</th><th>Continued damage</th><th>Breach formation</th><th>Breach widening</th></tr>
<tr><td>(4) Physically based models:
Surface erosion (non-cohesive, more erodible soils):</td><td>As above</td><td colspan="3">Different models use different erosion relationships, including linear excess stress; user needs to define soil erodibility and the soil critical shear stress (initiation of erosion) and/or other soil parameters (% fines, PI (plasticity index) etc)
Some models predefine process of erosion down and back through levee until breakthrough (eg AREBA), while others allow for breach erosion to be defined by the model (eg EMBREA)
Lateral widening rate can be based upon a multiple of breach bed erosion rate and may include soil wasting through block failure
Block failure calculated by looking at shear stress and rotational failure conditions, based upon a balance of forces acting on the soil</td></tr>
<tr><td>(4) Physically based models:
Zoned structures</td><td>As above</td><td colspan="3">No headcut-based models for zoned structures yet exist (commercially)
Surface erosion models for zoned structures do exist, but performance has not been validated as widely as for homogeneous structures; models use the same erosion equations, but allow for different rates of erosion in different zones and check for block failure due to undercutting erosion between zones
Zoned models demonstrate that breaching processes can be significantly different to those predicted for the same, but homogeneous structure</td></tr>
<tr><td>(4) Physically based models:
Rockfill materials</td><td>As above</td><td colspan="3">No commercial models exist for breach through rockfill materials; the definition of rockfill material also varies from user to user; it is recognised that the failure process of flow over and through clean, porous rockfill differs from that of finer and mixed graded materials
Application of a zoned erosion model, using a thin or erodible core, offers the best approximation to rockfill structure breach at the moment</td></tr>
</table>

Level of analysis/type of model or method	Physical processes: Initiation	Continued damage	Breach formation	Breach widening
(4) Physically based models: Internal erosion	Current breach models do not predict the onset of internal erosion; an initial flow path (and size of flow path) has to be assumed	Having defined an initial flow path and size, models use erosion equations to determine whether the flow rate is sufficient to continue and increase erosion	As erosion along the specified path progresses and the hole through the structure erodes, the stability of the overlying material is assessed until roof collapse is predicted; at this point the process reverts to open breach prediction	After roof collapse, breach widening follows the open breach method

3.2. Model application issues

3.2.1. ‘Stand-alone’ versus ‘integrated’ breach modelling

The breach formation process is highly dependent upon changes in hydraulic load conditions – whether upstream or downstream (see drowning below). When modelling a breach using a ‘stand-alone’ model, the effect of the breach formation and breach flow cannot be applied to the load conditions. For example, a breach through a levee in a river system will divert flow from the main river channel into the floodplain area. Unless the breach model is fully integrated with the flow model (at a time-step level) the breach prediction can only be a snapshot of potential failure at one time point; as soon as the breach develops, the balance of flow changes and the model no longer represents true conditions.

Some breach models allow for the inclusion of up and downstream flow boundaries (such as head time and stage volume relationships), but are rarely integrated within a flow model. In 2008 the HR BREACH model was fully integrated into the InfoWorksRS flow modelling package, allowing the prediction of breach in real time at multiple locations within the flow simulation. However, this combination of models has not been maintained in recent years.

Therefore, when using a breach model to predict flow conditions, attention is needed to assess how best to predict the flow boundary conditions leading to and arising from breach.

3.2.2. The importance of breach drowning by the downstream water level

Both downstream and upstream water levels play a significant role in breach initiation, formation and growth. When the downstream level is such that it affects flow through or over the dam or levee, it affects the rate of erosion and hence progression of breach. While some situations – such as a dam or levee in a steeply sloping valley – may allow for the downstream influence to be ignored, in most cases it plays an important role in determining the overall process.

3.2.3. Analysing the dominant processes

At present, models tend to simulate simplified scenarios; for example, assumptions are made of a homogeneous embankment or dam, with perhaps surface protection by rock or grass cover. The EMBREA model provides for the simulation of zoned embankments; however, no models allow for the assessment of features such as wave walls, drains, pipes or road coverings. Hence, when assessing a complex structure with a simplified model, it is first important to consider what the dominant processes of failure might be, and subsequently to simulate breaching of those aspects. For example, breach of a zoned embankment with a very large erosion-resistant core might be simulated by assuming only the core material exists, hence reducing the problem to a simple homogeneous structure. Such simplifications need to be considered carefully on a case-by-case basis.

3.2.4. Calibration

For fluvial river models it is normal to 'calibrate' the model by comparing the predicted hydrographs with observed floods. This is not normally possible for models predicting a breach hydrograph, so other methods are needed to validate use of the model or method. These may include:

- use of historical data to compare predictions against past events
- use of simple methods (peak flow equations) to compare 'ball park' timing and flow predicted by more complex methods
- ensuring that applicability of methods (simple or more complex) to site-specific conditions (soils, loading etc) has been previously investigated and validated

A particular issue which significantly affects breach prediction is the effect of drowning on breach growth and flow. Drowning is where the downstream (flooding) water level rises sufficiently to affect the rate of flow through the breach opening. This is particularly relevant to levee breach, where water in flooded areas can rapidly 'back up' and affect the breach. Local topography can also increase the speed with which this occurs. Simple methods such as peak flow equations do not take this process into account.

3.3. Prediction methods typically used in England and Wales

This section provides a brief overview of different breach prediction methods typically used in flood risk analysis and management processes in England and Wales.

3.3.1. Current uses

Section 3.3.2 provides a summary of different breach prediction methods used in England and Wales by different end users for different applications. The various applications include:

- flood risk assessments (local authorities supporting planning decisions)
- flood risk assessments (Environment Agency regions supporting flood risk management decisions)
- system risk modelling
- National Flood Risk Assessment (NaFRA)
- Long Term Investment Strategy (LTIS)
- Risk Assessment Field Tool (RAFT and RAFTplus)
- Quantitative Risk Assessment (QRA) for dam safety management (portfolio risk assessment)
- QRA for ten-yearly (Section 10) safety review under the Reservoirs Act
- part of ALARP (as low as reasonably practicable) assessment to decide magnitude/extent of safety works on dams
- emergency planning for reservoirs

It can be seen that different end users/applications adopt different levels of analysis; these choices are not necessarily related to the risks associated with the particular end use. The link between accuracy of breach method and end use becomes even further dissociated when initial modelling and mapping products are subsequently used for other applications.

An area where single flood risks have multiple end users is in the recent national reservoir flood mapping programme. Here, reservoir flood mapping is used to determine the category of risk for a reservoir (and hence actions needed to manage reservoir safety), plus land use planning downstream from the reservoir, plus emergency planning for the reservoir.

The majority of breach prediction methods used for reservoirs apply the methods set out in EA Report SC090001/R1 and R2 – 'Guide to risk assessment for reservoir safety management (RARS)' (Environment Agency 2013a, 2013b). These include:

- methods used to estimate the probability of failure due to overflow, which rely on factoring in the allowable velocity, as per CIRIA Report 116 (Hewlett and others, 1987)
- peak breach flow using empirical equations such as Froehlich (1995), or Xu and Zang (2009)

These analyses are typically used in ten-yearly safety reviews (Section 10 reports), in deciding the extent of works required where a spillway is undersized (ALARP analysis) and in portfolio risk assessments by the major water companies (most have now completed these).

3.3.2. Discussion

It can be seen that there is a wide range of approaches used for modelling breach in England and Wales, suggesting there should be scope for rationalising them if clear guidance was available on the range of tools available, data required and indicative budget cost for different levels of analysis. This has led to the recommendation for Project 1, guidance on level of analysis (see Appendix C).

Table 5: Examples of different breach prediction methods used in England and Wales

Application	Method	Comments
Local/regional flood risk assessment and management		
Natural Resources Wales and Environment Agency	Location based upon known low areas, weaknesses Breach width based upon type of defence and loading (ie Instant fixed dimensions) Design events based upon a % of event conditions plus climate change	Operational Instruction 303_09 Flood Risk Management: Strategic Flood Consequence Assessment for Wales, Environment Agency, 2009 Technical Advice Note (TAN) 15: Development and Flood Risk, Welsh Assembly Government, 2004
Planning studies	Increased complexity of analysis on a case-by-case basis	Where simple assumptions provide insufficient detail, more complex modelling is typically applied, particularly where 2D flow behaviour can influence outcomes
Accounting for residual uncertainty: updating the freeboard guide	Reference to increasing levels of prediction analysis and complexity linked to reliability of flood risk assessment	No specific approaches are defined, but it is inferred that more complex breach analyses relate to more reliable flood risk assessments
National flood risk assessment and management; asset management		
National Flood Risk Assessment (NaFRA)	Probability of breach occurrence based on limit state equations of surface layer performance; volume of water through breach based upon the assumed breach width plus eroded invert level; breach width estimated from simple multiple of defence length and magnitude of load	A combination of simple, empirical and semi-physically based methods combined; however, breach length is based upon a simple relationship to load condition and length of section – uncertainty therefore equivalent to simple methods

Application	Method	Comments
Long Term Investment Strategy (LTIS)	To date, LTIS has used NaFRA to calculate flood risk from rivers and sea in its various scenarios.	LTIS will use NaFRA2, but the "how" is yet to be finalised.
Risk Assessment Field Tool (RAFT and RAFTplus)	RAFT and RAFTplus are tools to support prioritisation of asset maintenance works; RAFT uses the same assumptions for breach as NaFRA.	RAFT only considers each asset individually, rather than system-wide as within NaFRA
Reservoir engineering		
RARS –Tier 1 (Qualitative)	Judgement to predict potential flood levels, based upon half height of dam and following contour maps	Basic judgement, with water level at dam based upon dam height
RARS – Tier 2 (Basic quantitative)	Froelich (1995) peak discharge equations combined with hydrograph estimation using the CIRIA Report C542. methodology.	At that time, Froelich (1995) offered the best simple estimation of likely peak outflow
RARS – Tier 3 (Quantitative)	Use of simple rapid breach prediction model (FRMRC) AREBA model (Van Damme and others, 2011) for entry-level analysis OR use of numerical breach growth prediction model (for example, HR BREACH and WinDAM)	Use of numerical models allowed for a more refined calculation of the flood hydrograph, using soil parameters and reservoir bathymetry

Application	Method	Comments
National reservoir flood mapping (2009)	Froelich (1995) peak discharge equations combined with hydrograph estimation	
National reservoir flood mapping (2016)	Xu and Zhang (2009) peak discharge equations combined with hydrograph estimation	Xu and Zhang was chosen to replace Froelich (1995) since it offered the opportunity to introduce a measure of soil erodibility into the calculations and also because USBR Hydraulic Laboratory Report HL-2014-02 recommended that it gave improved prediction, especially for dams less than about 15 m high
Small reservoirs simplified risk assessment methodology (EA FD2658)	The research produced simplified plots (based upon breach modelling) allowing estimation of flows according to reservoir and dam type	

3.4. Summary

This chapter has shown how current methods of estimating the magnitude and time to peak breach flow vary with user type and have significant variation in accuracy of the estimate.

It is considered that research is needed to allow a more informed decision by end users of breach modelling tools as to which method is most appropriate for their use and the uncertainty implicit in the selection of the method.

4. State of knowledge

This chapter provides a summary of the current state of knowledge in relation to key components or physical processes required for predicting breach initiation, formation and growth.

4.1. Historical development

Breach prediction methods have been under development for the last 60 years, with some early models dating back to the 1960s.

The first widely recognised commercial code was probably that of the NWS DAMBRK model, developed in the 1980s (Fread, 1988a,1988b). This flood routing model, designed specifically for dambreak analysis, came with a breach model that is still used by some researchers for performance comparison today.

During the 1980s and 90s a significant number of simple breach equations were developed by undertaking curve fitting to historical dam failure data. In 2004 Wahl undertook an in-depth analysis of these equations, publishing the Dam Safety Office (DSO) Report which gave an assessment of the relative accuracy and performance of these equations. At that time, the Froehlich equation (1995) was reported as the most reliable – albeit still with significant ranges of uncertainty.

A key limitation of the simple breach equations is the lack of consideration of structure type, geometry and soil type and state. In 2009 Xu and Zhang developed a more refined breach equation that takes soil erodibility (high, medium, low) into account. This is currently accepted (USBR Hydraulic Laboratory Report HL-2014-02) as the most reliable simple breach equation methodology, albeit still with considerable uncertainty.

During the late 1990s, as numerical modelling and computing capabilities advanced, a number of researchers developed numerical breach models, for example, Deich_P (Germany), SITES (USDA), NCP-BREACH (New Zealand), BRES (Netherlands), RUPRO (France), HR BREACH (UK) to name but a few.

In the USA, the USDA HERU at Stillwater pushed ahead with a programme of research into headcut erosion through earth embankments. This high-quality work led to the refinement of the SITES breach code, subsequently built into the WinDAM breach models (versions a, b, c etc) available today.

In the early 2000s, with the Floods Directive under development, the European Commission funded a number of research projects that helped to advance knowledge and understanding in relation to breach processes and flood risk. In particular, projects such as CADAM (Concerted action on dambreak modelling); IMPACT (Investigation of extreme flood processes and uncertainty); FLOODsite and FloodProBe (Technologies for the cost-effective flood protection of the built environment) were undertaken. IMPACT supported large-scale field and laboratory tests on breach processes, providing valuable test data;

FLOODsite supported the further analysis of this data and refinement of breach prediction methods.

Research under the EC FLOODsite programme also collaborated with the CEATI Dam Safety Interest Group breach modelling project which ran between 2004 and 2011. This project (managed by Tony Wahl of USBR and comprising many different national participants – both researchers and asset owner managers) (i) studied available breach models; (ii) explored available field, lab and historical data; (iii) undertook model validation exercises; (iv) concluded with recommendations as to the performance of the top 3 breach models and the next steps for research and development. At that time the recommendations focused on the WinDAM and HR BREACH models (USBR Report DSO-2017-02, 2017).

In the past 5–10 years breach models have continued to advance, and research has focused on understanding specific processes (e.g. internal erosion, soil erodibility, grass performance). The HR BREACH model has spawned the AREBA (simplified rapid model) and EMBREA (more complex, zoned embankment) models. In addition, other physically based models such as DL Breach have been developed. In the academic sector, more ambitious 2D and 3D integrated codes, combining seepage, soil stability, flow and erosion processes, are under development.

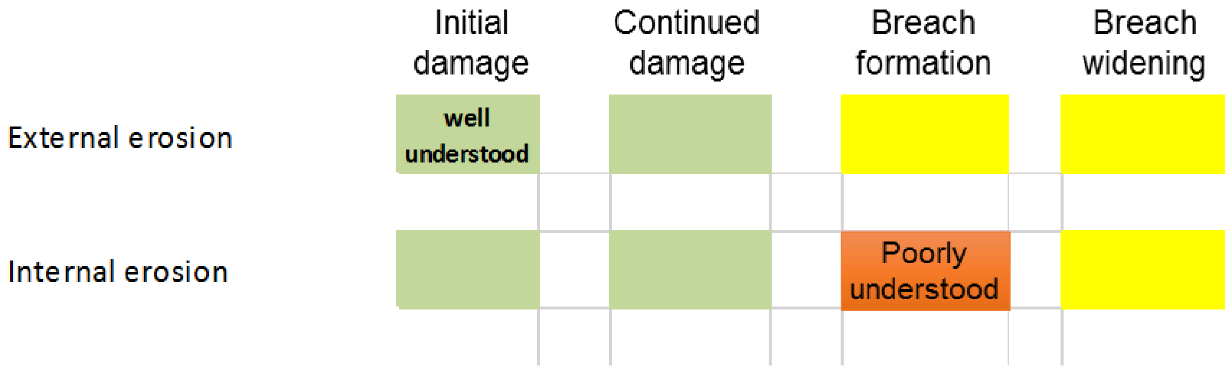
While some initiatives have focused on refining the breach prediction methods/models, a common underlying issue is the understanding and assessment of soil erodibility. All models – whether simple equations or complex 3D simulations – require an erosion relationship to be defined, which invariably looks at the erosion force of the flow and the erodibility of the soil. A clear understanding of soil erodibility, how to measure it and how natural and man-made variability occurs, remains elusive. Since this parameter underpins any refined breach method, it should be a priority for research action in the coming years.

Since breach prediction is quite a specialised topic, the number of long-term researchers in this field is limited, and they are well-known to each other. Periodic meetings to look at international progress and collaboration have taken place since the late 1990s. The most recent of these took place in Aussois, France, hosted by EDF in December 2017. This meeting looked at soil erosion (2 days) and rock erosion (2 days), identifying the current state of practice and priority areas for future research. For soil erosion, a key priority for action in the coming 1–3 years is understanding soil erodibility and how this affects the macro erosion process (i.e. from headcut through erosion-resistant soils, to surface erosion through more erodible soils and slumping through clean rockfill materials). A further priority is how the inclusion of fines within a clean grading affects the overall erodibility and macro behaviour. This knowledge would allow identification of the appropriate breach erosion model for a given application.

4.2. Current knowledge and gap analysis

One of the considerations in assessing the current state of knowledge, and where improvements are required, is whether all stages of breach are equally well understood, or whether one of the stages is less well understood and research of this aspect could provide a ‘quick win’.

Section 4.2.1 provides one overview of the current state of knowledge in relation to different breach processes. Another perspective is shown in Figure 42, which provides a possible simplified overview of the different stages in the breaching process. It uses colour coding to show a possible interpretation of the current state of knowledge, ranging from green (moderately well understood), yellow (gaps) to amber (poorly understood). Both link with the schedule of candidate research projects provided under Appendix B.



(Note that the purpose of this figure is to promote consideration and debate of our current state of knowledge, rather than being a definitive assessment)

Figure 42 - Diagram to show possible gap analysis in relation to stages of breach

As well as the level of knowledge and our ability to predict the processes in each of these sectors, the relevance or importance of the different sectors varies according to the different ‘end users’ (Figure 1). For example, using the category of end users shown in Figure 1, initial damage is of interest to asset managers, whereas continued damage and breach formation are of more interest to incident managers.

This matrix structure is part of the knowledge base used to identify and define potential research projects to improve our knowledge and tools to assess breach.

Prioritisation of different research actions requires consideration and weighting of a range of factors as detailed in Chapter 5 (road map and business case). The relevant importance of these different factors will invariably change over time as different priorities rise and fall.

A factor that will always affect the timing and priority for action is the potential to collaborate with other national or international initiatives, where common goals allow for sharing of costs and/or widening the reach of the research, data used, case studies applied etc. Details of current international research efforts have been included wherever possible.

Table 6: State of knowledge related to breach processes

Process	State of knowledge	What does this mean?	Implications
Breach initiation			
Grass performance	Guidance exists (CIRIA 116 report, 1987) based upon data from the 1970s. The guidance has limitations in scope and includes factors of safety. Guidance is based purely on grass condition and duration of overflow velocity. An Environment Agency grass and soil erosion project (SC140006) was previously initiated to scope and address current limitations in guidance (unpublished).	The limitation in range (nothing less than 1 m/s or more than 8 m/s) restricts applications. The inclusion of a factor of safety, which is not quantified, affects use for risk analyses. The use of a generalised grass condition ignores the aspect that a small defect in otherwise good cover can undermine the entire protection layer. The input parameters (velocity, duration and grass condition) ignore more recent knowledge about soil erodibility and different grass type performance against erosion.	Addressing these limitations would allow: - better understanding (and hence performance/risk analysis) of grass performance - greater use of designed (both type and maintenance) grass cover - clarity on where grass cover plays a greater or lesser role in overall performance
Rock performance	Good design guidance already exists.	Guidance advises on the design and performance of rock cover in relation to both wave and surface flow.	Addressing the design and performance of transitions would improve overall performance.

Process	State of knowledge	What does this mean?	Implications
		Poor attention to transition detail between rock cover and no cover is often the source of problems.	
Effect of transitions	Transitions are junctions between changing structures, cover, soil types etc. The risk arising from failure processes developing at transitions has not been widely recognised or addressed. A study into transitions is being undertaken by the Environment Agency (Expected publication 2021).	While dam and levee main features are well addressed, the increased risk of failure occurring at transitions can undermine the overall performance of the structure. Clarity on transition types, potential failure processes and how to assess, design for and address is needed.	The true risks arising from transitions have been underestimated in the past. Addressing the real risks posed by transitions will improve the overall risk management of dams and levees.

Process	State of knowledge	What does this mean?	Implications
Breach continuation			
Internal erosion processes	Recent advances in understanding from the EURCOLD working group/Bulletin 164 and US research defines 4–5 different processes.	Process understanding is established, but this has not been transferred into breach prediction models. Current models only predict erosion growth through a predefined route.	Model development to implement the new science is needed before industry models will become available.
Breach enlargement			
Rockfill erosion	Limited. Different definitions of rockfill in different countries plus a lack of clarity on how different coarse material erodes.	Research needed to clarify erosion processes before breach models can incorporate the science.	Current application of breach models to rock fill dams requires careful judgement on modelling assumptions.
Coarse material surface erosion	Erosion relationship and macro erosion processes not yet publicly validated against large-scale field data.	Unclear where macro erosion processes change in relation to soil type and state. Research needed to confirm how soil erodibility varies with soil grading and how macro erosion processes vary with soil erodibility.	Care needed when applying existing breach models to ensure that the most appropriate processes are being applied.
Clayey material headcut erosion	Process of headcut has been researched and validated against high-quality large-scale field tests.	Headcut erosion model exists within the public domain.	Not a priority for further research.

Process	State of knowledge	What does this mean?	Implications
Internal erosion	Recent advances in understanding from the EURCOLD working group/Bulletin 164 and US research defines 4–5 different processes.	Process understanding is established, but this has not been transferred into breach prediction models. Current models only predict erosion growth through a predefined route.	Model development to implement the new science is needed before industry models will become available.
Arching	Some studies into arching effects in general, but limited with regard to internal erosion.	Only basic processes are included in breach models – if at all.	Timing of roof collapse and transition to open breach will be uncertain.
Drowning effects	Weir drowning processes are well-understood and broadly applicable – albeit under changing flow conditions. The impact of drowning on breach processes is significant.	Breach models or analysis should take drowning into consideration.	Analyses that ignore potential drowning effects will over predict the rate of breach growth and rate of floodwater release.
Scour hole effects	The reason for development and their impact on breach prediction is poorly researched.	Most breach models ignore erosion below the foundation level and do not take the effects of scour holes into consideration.	Due to the interactive nature of breach growth, it is unclear what the magnitude or effect inclusion of scour holes in breach prediction may have. Research is needed.
Zoned/complex structure effects	Recent models such as EMBREA have introduced the option of	Zoned breach models have demonstrated that the effect of layers or zones of	The demonstration of high potential impact on breach results

Process	State of knowledge	What does this mean?	Implications
	predicting breach through zoned structures. This requires predictions as to how different layers or zones of material may respond. Such models are not yet internationally validated.	different material erodibility can be very significant.	means that it is important to take zones into account when modelling breach. Hence, international validation of the performance of zoned breach models is needed.
Breach widening			
Rates of widening	Knowledge is limited/moderate. Most breach models predict the rate of widening as a fixed function of the rate of bed erosion.	Rate of widening prediction within breach models is limited and has not been widely validated.	Prediction of ultimate breach width and rate of growth not validated.

4.3. Calibration of breach modelling

The calibration of breach modelling is more difficult than for 'standard' flow modelling, since it is difficult to obtain detailed case study data sets for a range of different structures and scenarios. When breaching of dams or levees occurs, it is typically during extreme storm conditions, or as a 'surprise' (eg 'sunny day' dam failure). In either case, little time or priority is given to data collection. As such, breach model performance relies upon international validation through projects such as the DSIG breach modelling project (see USBR [2017]), where laboratory or field test data sets are used to calibrate or validate models.

The challenge for finding useful data sets for model calibration is often a balance between the scale of any tests and data detail and quality. Many research projects are undertaken at very small scales (eg in a flume on a sample levee 0.2–3m high). While reliable data can be collected, at this scale it is difficult to correctly reproduce all of the processes that occur during breach formation. Conversely, when a real levee or dam breaches, detail is rarely recorded showing water levels, flows and the pattern of erosion.

Different researchers and organisations have undertaken various efforts over the past decade or so to collect data against which to develop and calibrate/validate breach prediction methods. These include:

- USBR (2017) (CEATI Dam Safety Interest Group [DSIG] breach modelling project)
- EC IMPACT project (www.impact-project.net)
- Electricité de France (EDF-CIH)
- TU Delft
- Froehlich, Xu and Zhang

4.4. Probabilistic approaches and fragility curves

The main focus for breach prediction research has tended to be process-based to date. This perhaps reflects the uncertainty amongst researchers and industry practitioners regarding the behaviour of breach through different structures, which requires consideration of integrated hydraulic, soil and structure behaviour. In addition, a key factor dictating the rate and nature of erosion is the soil erodibility, but no clear definition of erodibility (and all of the soil parameters affecting it) has yet been agreed.

Probabilistic approaches to predicting breach formation can embrace the uncertainty surrounding the processes. For system risk modelling, 'fragility curves' relating the likelihood of failure to hydraulic load conditions can be developed. Curves can represent specific physical processes (eg seepage) or a combination of processes. Fragility curves do not, however, detail the progressive physical processes of breach formation – that is, the processes that occur once failure begins, and which determine the rate and characteristics of the breach flood hydrograph.

However, application of breach process models using Monte Carlo simulation, with appropriate distributions for modelling and load parameters – in particular soil (and hence erodibility) parameters, does provide a distribution of breach results which then allows the user to understand how the breach formation process may vary.

4.5. Cross-cutting issues and topics

With various different research initiatives listed, and an ongoing programme of research supporting flood risk analysis and management always underway, the constant risk is that inconsistencies arise between projects in relation to underlying assumptions, parameters used and so on.

4.5.1. Soil erodibility

Soil erodibility is a key driver for all stages of breach. The current state of knowledge and methods used have been explained in the previous sections of this report. It is recommended that a consistent approach to soil erodibility is used across all Environment Agency research projects – for example, when considering reservoir drawdown, soil and grass performance etc.

4.5.2. Transport embankments

Given the number of transport embankments (road, rail etc) that exist within and are aligned across flood risk areas, it is worth summarising the current state of knowledge and implications that these structures have on flood risk analyses.

Transport embankments are rarely constructed as flood defence structures; hence the soil may be more susceptible to erosion because:

- exposed surfaces may not be protected from flowing water
- soil grading may not be designed to withstand a hydraulic gradient (ie high seepage rates)
- embankment structures may not be able to withstand a high retained level of water
- structures through and across the embankment may not be designed to withstand flowing water

In extreme floods, it is likely that some of these embankments will provide informal flood attenuation by impounding water upstream when inflows exceed the size of the culvert through the embankment. It is noted that historically (canals and railways) cross-drainage culverts were only designed to pass a 1 in 30 chance per year flood, although at more recent infrastructure embankments the cross-drainage is generally designed for a 1 in 100 chance.

The implications of this is that when such embankments are being used as flood defence structures, their performance is unlikely to be as good as that of a designed flood defence. Rates of erosion and modes of failure may be more rapid than expected.

Research into zoned structures, transitions and the erosion of coarser-grained materials can provide knowledge that would help make better informed predictions as to how such structures would breach.

4.5.3. Routing of dambreak floods along downstream valley

Although this is strictly outside the scope of this project, it is important to appreciate that routing of dambreak flow down a valley varies from fluvial flood modelling for several reasons, including:

a) the flow hydrograph can be a shorter duration but with a much higher flow than normal fluvial floods
b) consequentially the breach hydrograph may be affected by debris capture and blockage of bridges etc.

Historical case studies (typically from the US) often show photos and recount experiences where huge amounts of debris have been washed along by the dambreak flow. Research under the EC CADAM and IMPACT projects also investigated and simulated these processes.

For more information see:
http://www.floodsite.net/html/taskinfo/57_CADAMIMPACTFLOODsite.pdf

Over the past decade, the complexity of numerical flow models has improved in parallel with the increase in computer processing power. Full hydraulic solutions to the St Venant flow equations are now more routinely used, providing better solutions to predicting the extreme hydraulic conditions that can occur during a dambreak. The key issues affecting the accuracy of dambreak modelling (assuming use of a suitable hydraulic model) are therefore:

- resolution and accuracy of the digital ground model
- inclusion (or not) of development features such as buildings, transport infrastructure etc
- ability to predict secondary breaching of structures retaining floodwater (such as infrastructure embankments etc)

The degree to which these issues are addressed is often dictated by cost. Allowing for the effects of debris transport, erosion, deposition and blockage remain issues typically requiring specialist expertise (and hence further cost).

4.6. Relevance of international research for application in the UK

As this report has highlighted, there are many different aspects and processes related to breach prediction, with varying degrees of existing knowledge and practice. At an international level, various programmes of research (for example, Defra / Environment Agency Flood and Coastal Erosion Risk Management R&D programme, USBR) are underway that focus on different aspects of breach, with the goal of improving different national capabilities underpinning flood risk management. Some of these research efforts will be of direct value to the UK, with others less so, depending upon their focus.

While collaborating in research at an international level often provides an opportunity to achieve research goals at a lower cost, and to use internationally recognised facilities and expertise, there can also be drawbacks, including:

- whether the focus of work aligns with priorities identified for the UK
- whether the conditions being researched directly applicable to conditions found in the UK
- whether there open access to the research results, which allows the work to be shared across the UK industry

The second of these points is particularly relevant. Research efforts focusing on generic underlying processes, such as soil erodibility or macro erosion processes, are typically of direct value to the UK, since the same problems and processes occur in the UK. However, research focusing on the performance of dams and levees, where the design, construction or protection layers are country-specific, are less valuable. Examples of these include research into vegetation/grass cover, where the vegetation is country/climate-specific and research into the failure of Dutch/German levees, where their specific design of clay covering a sand core means that the failure process will differ from that of UK levees, which are typically constructed from soil throughout.

Hence, where international research opportunities are noted, it is important to assess the direct and indirect relevance of the work to UK application before looking more closely at the collaboration options.

4.7. Summary

This chapter has summarised historical development and current understanding of factors governing the timing and magnitude of peak breach flow and highlighted that some stages of the breach process are less well understood than others (Figure 42).

An understanding of the current areas of uncertainty in knowledge, and the impact of this on user needs, is important in defining priorities for research.

5. Suggested case and road map for research into breach, for England and Wales

5.1. Introduction

This chapter brings together the business needs of asset owners and the existing state of knowledge and tools for breach analysis to define research needs and priorities for England and Wales. It also provides a high-level plan (road map) to improve tools for the assessment of breach in embankment dams and levees. This scoping has been limited to the breach of earth embankments (and associated appurtenant structures) and has not considered concrete or other forms of dams, or flood defence walls (for instance, gravity, sheet-piled).

5.2. Current knowledge

Figure 43 provides an overview of the stages in the breach process and significance to the structural integrity of the embankment retaining water. It was initially thought that projects might be prioritised by stage of breach, partly as the state of knowledge varies with each stage and also this would have allowed prioritisation by end use, but this proved impractical as the physical processes often span several stages of breach.

5.3. Overview of business needs

5.3.1. General

The first step in assessing the case for research to improve breach prediction is to understand the business needs of asset owners, and which of these are affected by an understanding and modelling of breach.

User needs can be subdivided in a variety of ways, but would ideally match the different stages of breach as these relate directly to user needs (as shown in Section 1.2). However, this type of classification is impractical given our current state of knowledge, so instead Table 7 shows the needs of asset owners subdivided by theme. In this table the term ‘breach’ is used to mean complete collapse of a structure leading to escape of the retained water.

Users need a tiered set of tools to reflect the wide range of sizes and hazard of dams and levees, understanding how breach contributes to managing dams and levees. Although views on what constitutes an appropriate tool and its potential application are likely to vary widely.

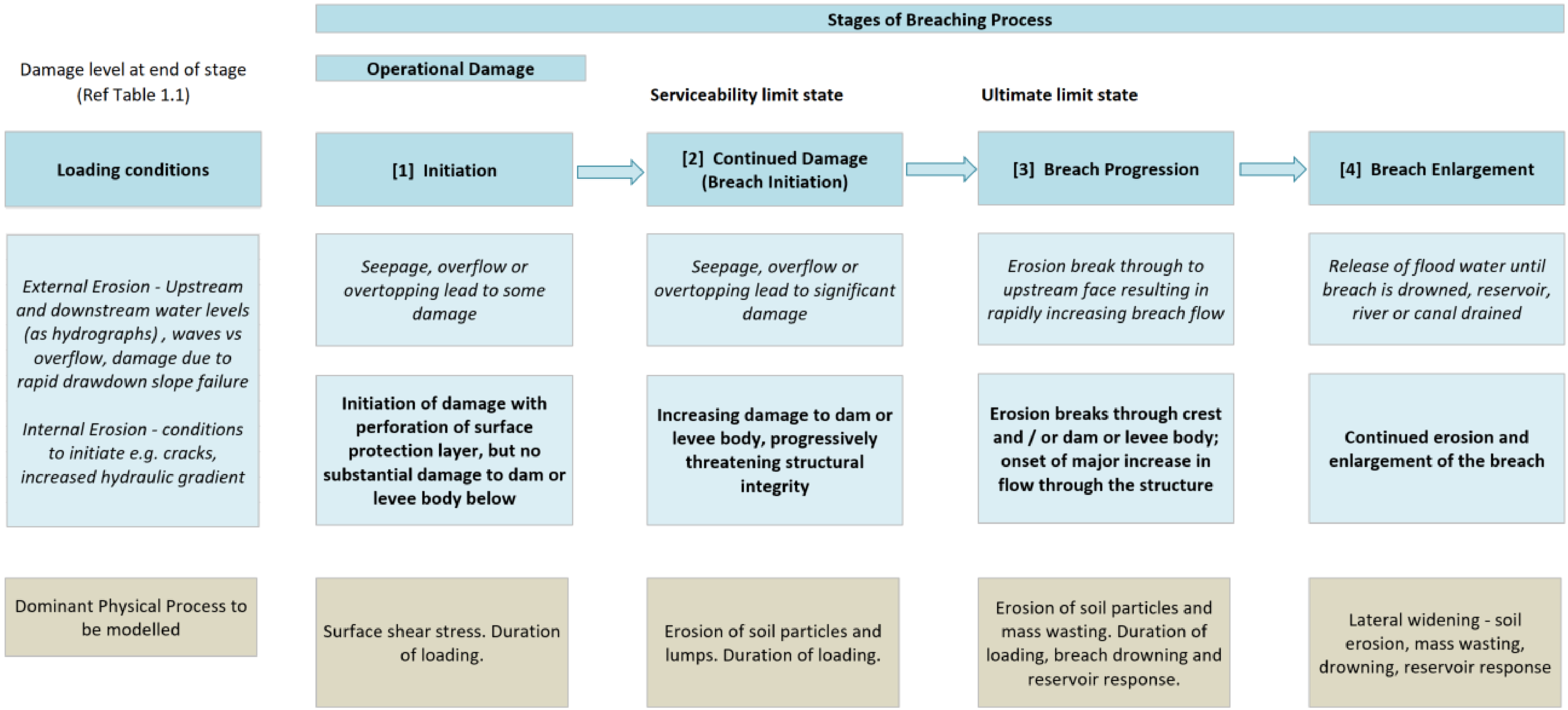


Figure 43 - Key stages of the breaching process and erosion mechanisms

Table 7: Needs of asset managers affected by understanding of breach processes

Theme	Engineering tools		Investment decisions	
	Management decisions	Surveillance/ monitoring	CAPEX	OPEX
Policy, strategy and investment	Is existing risk of breach tolerable? Are existing tools to asses risk of breach adequate, or do we need more detailed analysis?	Frequency of surveillance	Where should existing risk of breach be reduced?	Optimise use of existing assets?
Asset manage-ment	Key failure modes that could lead to breach? What is annual probability of damage/breach? Relative risk – which structure(s) is/are most vulnerable to breach?	Methods of surveillance (condition indicators)?	Upgrade the dam/ levee to increase resilience to breach	Maintenance/ improvement of existing surface cover (e.g. to facilitate surveillance)
Incident manage-ment and modelling	Likelihood and time to breach? Consequences of breach Time to evacuate?		Dams – increase installed drawdown capacity Levees – warning time	Emergency plans Operability of emergency drawdown facilities
New dams/ levees	Balance between 'construction of new assets' and 'operation/maintenance of existing assets' (CAPEX and OPEX)?			

Table 8: Tiered approach for breach prediction methods

Tier	Basis	Example of tool	Example of application
1	Qualitative	Rule of thumb	Screening either by panel engineer in Reservoirs Act Section 10 assessment, or by owner of a portfolio
2	Simple quantitative	Simple equations, ideally allowing for soil erodibility (e.g. Xu and Zhang)	National flood mapping Fragility curves
3	Quantitative	Breach model	Owner's assessment of risk and emergency plans at individual very high consequence (LLOL > 100) dams and levees

Note: LLOL = likely loss of life.

5.3.2. Policy makers and decision takers

Each year reservoir safety incidents are reported at dams in England, as detailed in Environment Agency incident reports (https://www.gov.uk/government/publications/reservoir-safety-post-incident-annual-report-2014, accessed Sep 2020). These are defined as situations that if left without any intervention may lead to failure. Although complete failure, or a full breach is extremely rare and the safety record very good, the reservoirs are aging and climate conditions changing. So research is needed to help understand which events are likely to be limited to damage and which could progress rapidly to breach, release of the reservoir water and consequent flooding. Similarly, with significant floods there are sometimes structural failures of flood defences (levees), sometimes below the design standard. These are reported in periodic review reports.

The decision on how to build new (or upgrade existing) assets that are resilient to breach, and the risk posed by existing assets, can only be as effective as the underpinning knowledge of breach processes. Advancing understanding of failure processes, both in terms of stages of evolution and absolute soil erodibility, will improve risk management by allowing a better assessment of the risk and more targeted solutions to manage that risk.

The decision as to when improvements to dams and levees to reduce the risk of breach are worthwhile needs a realistic understanding of:

- the cost of construction and maintenance of these assets
- the risk of failure (breach), which includes understanding the magnitude of the potential breach flow (this report) and the impact on people

- when it is appropriate to decommission an asset – for dams where the hazard and risk of failure to people outweigh the benefit to society, or where the maintenance (and/or) upgrade costs can no longer be justified in terms of benefits.

In the UK around 17 new dams are currently built each year, with around half that number decommissioned. Similarly, the UK population of flood defence assets is being added to and reduced each year. Design and construction of these new assets, and their decommissioning, are carried out most effectively when engineers have a good appreciation of breach processes and can thus provide reliable information to decision takers.

Climate change means that more frequent and extreme flood loading will occur, as well as periods of drought. Understanding how soil erodibility responds and changes under such conditions is essential for managing these increased risks and for ensuring dam and levee resilience into the future. For example, a levee that has been dry for many months, and is then subjected to extreme flood conditions, may not behave in the same way as one that had remained reasonably moist prior to flooding.

Since many countries face the same challenges, international collaboration to advance knowledge and understanding is an effective option. However, while many of the fundamental processes are common, it should be recognised that asset design and vegetation type (and hence performance) can vary from country to country, so care is needed to focus any collaborative efforts on aspects that are relevant to the UK dam and levee stock. For example, a coastal levee in the Netherlands is likely to be of a design not typically found in the UK.

Similarly, third-party embankments – such as road and railway embankments – are typically not designed or constructed to act as flood-retaining structures and should not be assumed as such. However, since many such structures run along and across river valleys, they are often subject to flooding and can retain floodwater. In these situations, understanding how these structures may erode and fail becomes equally important, since their failure can result in surges of floodwater. Here we are faced with the same need to better understand soil erosion processes, and the absolute erodibility, but for a wider range of material types and construction quality.

5.3.3. Asset managers

Different breach erosion mechanisms affect how floodwater is released. The different erosion processes affect the timing of catastrophic failure, as well as the progressive release of water up to that point. This is likely to affect flood impacts that are the basis for flood risk calculations and may also underpin justifications for investment in the area.

Since different remedial measures by asset managers may be appropriate in different situations, the cost of such works becomes dependent upon having a clear understanding of the structure and how it might erode such that the most appropriate cost-effective measures are applied.

Recognising that different soils erode at different rates and in different ways means that structures can and should be designed and managed in ways that relate to their potential failure modes. It may be permissible for structures that are less erodible to be exposed to limited overflow and some soil erosion, which for structures that are more erodible would be catastrophic. Hence, carrying out research to improve confidence in which erosion processes would occur in which soil types and conditions would allow for a more site-specific response to be made when dealing with asset damage.

5.3.4. Emergency planners and incident managers

For managing emergencies, and taking steps to limit and control the breach, the timing, nature and rate of growth of the breach are all factors that will influence how best to limit and control further breach growth. Research to improve knowledge of these processes and understanding of how breach evolves through specific soil types and states will therefore improve the accuracy of emergency plans and the effectiveness of incident response measures.

Understanding what process might occur, and the timing and nature of any flood release, is fundamental for effective emergency planning and event management. The nature of the flood hydrograph (as dictated by the soil erodibility and erosion behaviour) will determine how destructive, how quick and how far downstream effects might be felt. It is particularly important for conditions nearer to the breach site. In the extreme, the dam or levee may either retain water under overflow conditions until a sudden catastrophic failure occurs, or it may progressively erode and release water resulting in a slower but more manageable, less destructive release of floodwater.

5.4. Candidate research projects

5.4.1. Project identification

A number of candidate research projects have been identified as shown in Appendix B. These have been identified from the review in the preceding chapters and discussions arising from the Aussois EDF led workshop on overflow erosion in December 2017 (as part of an International Commission of Dams (ICOLD) sub working group). The schedule in Appendix B includes columns for type of project (scoping, laboratory, field etc), type of erosion and soil type. They are limited to what may be a reasonable set of objectives over the next 10 years.

Table 9: Summary of candidate research projects (fully described in Appendix B)

Project	
Ref	**Title**
1	Sensitivity studies, guidance on level of analysis and risk-based approaches
2a	Erodibility variability of UK soils – Stage 1 Scoping
2b	Erodibility variability of UK soils – Stage 2 Owner consultation and field testing
3	Measures to inhibit breach in existing and new earth structures
4	Review and update of 2018 breach scoping project
5	Standard specification for tests for soil erodibility
6	Understanding the progression of surface erosion through the analysis of dominant soil erosion processes
7	Developing and validating soil erosion model(s) for coarser-grained materials
8a	Grass cover – Index parameters to allow comparison between sites
8b	Performance of grass cover – Phase 2 Lab and field
8c	Performance of grass cover – Phase 2 Reinforcing systems
9	Understanding the progression of internal erosion from initiation through to breach formation
10	Performance assessment existing internal erosion breach models/ processes
11	Development of internal erosion breach models (ICOLD Bulletin)
12a	Performance assessment of existing zoned breach models – External erosion (Phase 1)
12b	Refine/update zoned breach models – External erosion (Phase 2)
12c	Performance assessment of zoned breach models – Internal erosion
12d	Refine/update zoned breach models – Internal erosion (Phase 2)
13	Wave-induced breach
14	Impact of slope instability on vulnerability to external erosion
15	The effect of scour holes during breach
16	Effect of temperature on seepage, soil erodibility and vulnerability to internal erosion
17	Performance of transport embankments
18	Linking geotechnical stability and breach formation process models

This results in a range of projects that would aid development of breach prediction capability, through both internal and external erosion processes, and across simple and more complex zoned structures.

A number of projects related to breach have already been identified under the reservoir safety research strategy (Environment Agency, 2015), but for simplicity are not included in the schedule in Appendix B.

Table 10: Summary of existing projects in reservoir safety research strategy

Project No.	Title
2015-02	Management of trees
2015-05	Leakage and seepage
2015-6	Monitoring and surveillance
2015-7	Geophysics
2015-14	Digital Elevation Model (DEM) – Imperial/Sheffield (Note: SERC-funded project)

5.5. Costs and benefits of research into breach

5.5.1. Costs of proposed research programme into breach

The outline programme of possible research actions shown in Section 5.4.1 above has an indicative overall cost of £4 million over 10 years (see Appendix C for details), or an average cost of £400,000 per year. . There is no commitment to undertake research to this value within this period. The research is suggestive and it is recognised that research on breach is just one topic within many for improving the management of flood related assets.

5.5.2. Benefits of research into breach

General

The outline case for carrying out research into breach includes:

a) improving the accuracy of existing flood risk assessments and reducing uncertainty in understanding them
b) optimising management of existing assets by improved assessment of magnitude of probability and consequences of failure, leading to more efficient structural upgrades (CAPEX) and operation/maintenance of existing assets (OPEX) spend
c) improved emergency planning, including plans that provide realistic expectations of warning times and actions that could be taken to avoid casualties and minimise damage

However, quantifying these benefits is problematic. It was initially hoped that individual proposed research projects could be linked to the stages of breach shown in Figure 43, but it proved difficult to assign projects to a single breach stage. The benefits have therefore been assessed, and are discussed below, as global benefits from improved tools for breach analysis, rather than being linked to individual research projects.

Realisation of these benefits would require additional investment in testing of erodibility of UK soils in dams and levees, which would include development of a commercial capability for laboratory (and/or field) testing of erodibility. The potential market and viability of such a capability is discussed in Appendix D, and the costs have been allowed for when estimating the net benefit of research into breach.

Current annual construction of new assets (CAPEX) and operation/maintenance of existing assets (OPEX) on dams and levees

England has around 2,000 dams retaining reservoirs large enough to come under current reservoir safety legislation, and around 9,000 kilometres of levees.

As part of this project the reservoir safety managers at 3 major water companies were asked for the annual average cost of maintaining their dams. This amounts to a total of the order of £98,000 per dam per year, broken down into construction of new assets (CAPEX) and operation/maintenance of existing assets (OPEX) as shown in Table 14. The cost of maintaining a smaller reservoir, more representative of private owners, fishing clubs etc, is assessed with best expert judgment at around 25% of this, at £25,000 per year. This reflects both recurring annual costs, plus periodic capital costs of major repairs and/or repairs following ten-yearly safety inspections under the Reservoirs Act. When multiplied by the number of dams in England, this gives an average annual cost in England of existing assets of around £70 million per year. In addition, around 17 new reservoirs are built each year, including flood storage reservoirs and farm reservoirs (to reduce summer abstractions etc), which could amount to an annual investment of £17 million per year. If Wales and Scotland were added, expert judgement suggests this could increase by the order of, say, 50%.

The equivalent total annual figures for all levees in England is estimated as £860 million per year, broken down as shown in Table 15 in Appendix D.

This gives an annual average cost in England of approximately £945 million per year.

Benefits as savings in operation/maintenance of existing assets (OPEX)

A better understanding of failure modes that could lead to breach would allow a more targeted approach to upgrading existing assets to rectify known deficiencies or works to increase the design standard of protection. This will become increasingly important as the effects of climate change and understanding of uncertainty in flood risk are improved. It is conservatively assessed that this could amount to a 1% saving in the annual average cost of upgrades, or £4.3 million per year, mainly through averting upgrades where it can be shown that the levee or dam is sufficiently resilient to breach. The 1% is a conservative value as the percentages are not clear, but it is made through expert judgement. There would be the costs of characterising the sites in terms of vulnerability to breach, which could be of the order of 5% of the cost of the works avoided, which would give a net saving of £3.9 million per year.

The benefits of breach research to the cost of providing new assets, and repairs after incidents, are more difficult to quantify. On the one hand, such research should lead to increased resilience and thus provide benefits through incidents averted. On the other, however, the improved understanding of breach may increase operation/maintenance of existing assets (OPEX) for new build and repairs. For this scoping project, no direct OPEX benefit has been assigned to the effects of breach research on design and construction of new build. The outcomes will be dependent on the availability of the research.

Benefits as savings in construction of new assets (CAPEX)

Implementation of the proposed research into breach would allow implementation of a risk-based approach to prioritising surveillance and maintenance, in that dams and levees that are resilient to breach (collapse with release of the retained water) could have a lower surveillance frequency, reducing the cost of surveillance by, say, 5% and maintenance by, say, 1% per year. These percentages are estimated through expert judgement. It is likely that capped maintenance budgets risk sub-optimal annual maintenance which may cost more in the long run.

For reservoirs the benefits of the research would be realised by taking resilience to breach into consideration when assessing which reservoirs are high risk. For the purpose of estimating savings this is estimated as an allowance of a further 5% of large reservoirs to be designated as 'not high risk', which would equate to approximately 100 reservoirs. The saving in relation to the cost of regulating a reservoir is therefore estimated as £6,800 per year for high-risk reservoirs, less a further £3,130 per year for "not high risk" (Defra (Mott MacDonald), FD2701, 2018). This would require a one-off ground investigation to characterise the site and test the erodibility of materials, which could cost, say, £15k per reservoir if carried out as part of a group, which over a 10-year period would give a saving of, say, £22,000 per year.

Benefits as reduced risk of loss of life

The greatest benefit from the candidate research is a better understanding of risk to people from escape of retained water (whether stored in a reservoir, or elevated in rivers and seas during floods), allowing more effective uses of available funds. Traditionally the economics of flood defences have been based on the risk of property damage, but a risk-based approach would also consider risk to life. The proposed research would allow reduction in risk to life by:

a) categorising dams and levees into those that are vulnerable to rapid failure, and those that would fail more slowly, thus having a smaller peak flow and increased warning times
b) making the case for upgrading vulnerable assets
c) allowing more effective emergency planning, with more realistic estimates of time before the floodwater would reach the population at risk, and thus increased evacuation efficiency.

An estimate has been given in Appendix D of the overall risk to life from dams and levees in England. It has inevitably made significant simplifying assumptions and so is only an order of magnitude estimate. Nevertheless, it suggests an annual life loss of around 16 lives (with no warning/ evacuation). Considering what would be a proportionate cost to reduce this risk as low as reasonably practicable, halving the probability of failure would amount to an estimated total cost of £1.8 billion. To lessen the probability you could improve the understanding of which dams and levees are vulnerable to rapid breach and which are resistant (resilient) so that upgrades/warning could be targeted. Although not used directly in the benefit–cost ratio below, it provides an independent estimate that the risk to life from a dam is significant, and that a better understanding of which dams and levees are resilient to breach would significantly reduce that risk to UK.

5.5.3. Benefit–cost ratio

Based on the above best judgement estimates of research costs of £400,000 per year for 10 years, and benefits per year of £4.44 million the benefits significantly outweigh costs.

Table 11: Potential benefits of research into breach (estimates based on author best judgement)

Number	Aspect of current expenditure	Key stage in Breach (Section 1.2)	Indicative potential annual benefits – value in £k per year and basis	Additional costs to realise these benefits – value in £k per year and basis	Net benefit – value in £k per year
1	Savings in OPEX from improved tools				
1.1	a) to understand which assets are resilient and reduce number of upgrades	Stage 3	£4,300 – 1% per year of precautionary capital spend	£430 – ground investigation to identify embankment construction, say 10% of savings	£3,870
1.2	b) design and construction of new flood management assets, and repair after incidents	All	Nil – Savings made in incidents averted		
2	Savings in OPEX from improved tools				
2.1	Surveillance		£20 – 5% of surveillance cost		£20
2.2	Maintenance	Stage 1	£330 – 1% of annual cost		£330
2.3	Emergency planning/forecasting				
2.4	Reduced number of 'high-risk' reservoirs which require regulation under the Reservoirs Act	Stage 4 – peak breach flow	£370 – assume another 5% (100) could be classed as 'not high-risk'	£150 – One-off cost of GI of £15k spread over ten years	£220
3	Savings in reduced risk to life				
	See main text. Used as alternative calculation to above.				
TOTAL			£5,020	£580	£4,440

Notes:

a) Values as annual average, as the risk management process is one of continuous improvement, rather than a fixed journey with single destination.
b) This neglects any benefits of a better understanding of breach processes on other embankments which may impound water such as canals, transportation embankments (accidental impounding when culverts block and/or during extreme rainfall events) and tailings dams

5.6. Suggested road map to deliver research needed

5.6.1. Introduction

The above assessment has shown that research into breach of dams and levees would provide an overall saving to the UK economy, in that the benefits significantly outweigh the costs. This section therefore sets out a suggested road map to deliver this research and associated benefits. The vision for this road map is:

That in ten years' time the science and engineering tools relevant to UK dams and levees will have improved substantially and contribute to managing all forms of flood risk. In addition, the engineering professions and others involved in managing water-retaining assets will have a better and more consistent understanding of breach processes and be applying these in their management of all forms of built infrastructure.

5.6.2. Prioritisation of projects and outline programme

When prioritising projects, a variety of factors need to be considered – many of which will vary over time. Two approaches to prioritising the candidate projects in Appendix B were therefore adopted.

Firstly, each project was given a ranked score (projects scored in the schedule in Appendix B, using the scoring system below) to reflect their value to the UK, in terms of their benefits to improving the science and/or tools, following the evaluation system.

Table 12: Scheme used to prioritise benefits of candidate research projects relating to breach

Score	Scored from consideration of both of the following	
	Science	Tools
9	Leads directly to improved science/understanding of core breach process	Produces an engineering tool of direct benefit to significant number of users and asset types
5	Part of refining science/building block within a specialist aspect of breach	Produces a tool relevant to a specific asset type
1	No direct contribution to improvement in science	No direct tool

Secondly, in addition to the absolute prioritisation, the different candidate projects are placed in one of 6 groups, comprising:

1. Associated projects already underway
2. Guidance
3. Erodibility parameters and dominant processes
4. Refining breach models
5. Refining specific aspects

6. Future modelling approaches

Of particular value will be opportunities for collaborative international research, where cost sharing and access to international expertise and datasets are attractive. With this in mind, the 10-year schedule shows indicative and relative priorities by groups of action; the specific order of individual actions will require periodic review to maximise value from opportunities.

Guidance

The 3 actions listed within this group are relatively small actions proposed to provide guidance to practitioners while the wider programme of research is undertaken.

Erodibility parameters and dominant processes

The 4 actions listed here are considered to be the highest priority actions needed. Three focus on improving understanding of different aspects of soil erodibility, which are fundamental processes driving the breach initiation and formation processes. The fourth addresses the need for defining a measure of grass cover performance, which would support later progression of the grass and soil erosion project (underway).

Refining breach models

6 actions are proposed that address model performance and model development covering internal erosion for simple structures and then both internal erosion and surface erosion for zoned structures. The actions proposed here logically follow after completion of No. 5.

Refining specific aspects

7 actions are listed. The performance of grass cover and grass reinforcement systems follow earlier actions Nos. 3a, 5 and 8. All of the other actions address individual specific issues and can be undertaken independently as shown.

Future modelling approaches

As the title suggests, this is a longer-term goal that is likely to evolve through further academic research and development work.

This resulted in the outline programme shown in Figure 44 below. The scope for the priority projects is included in Appendix C.

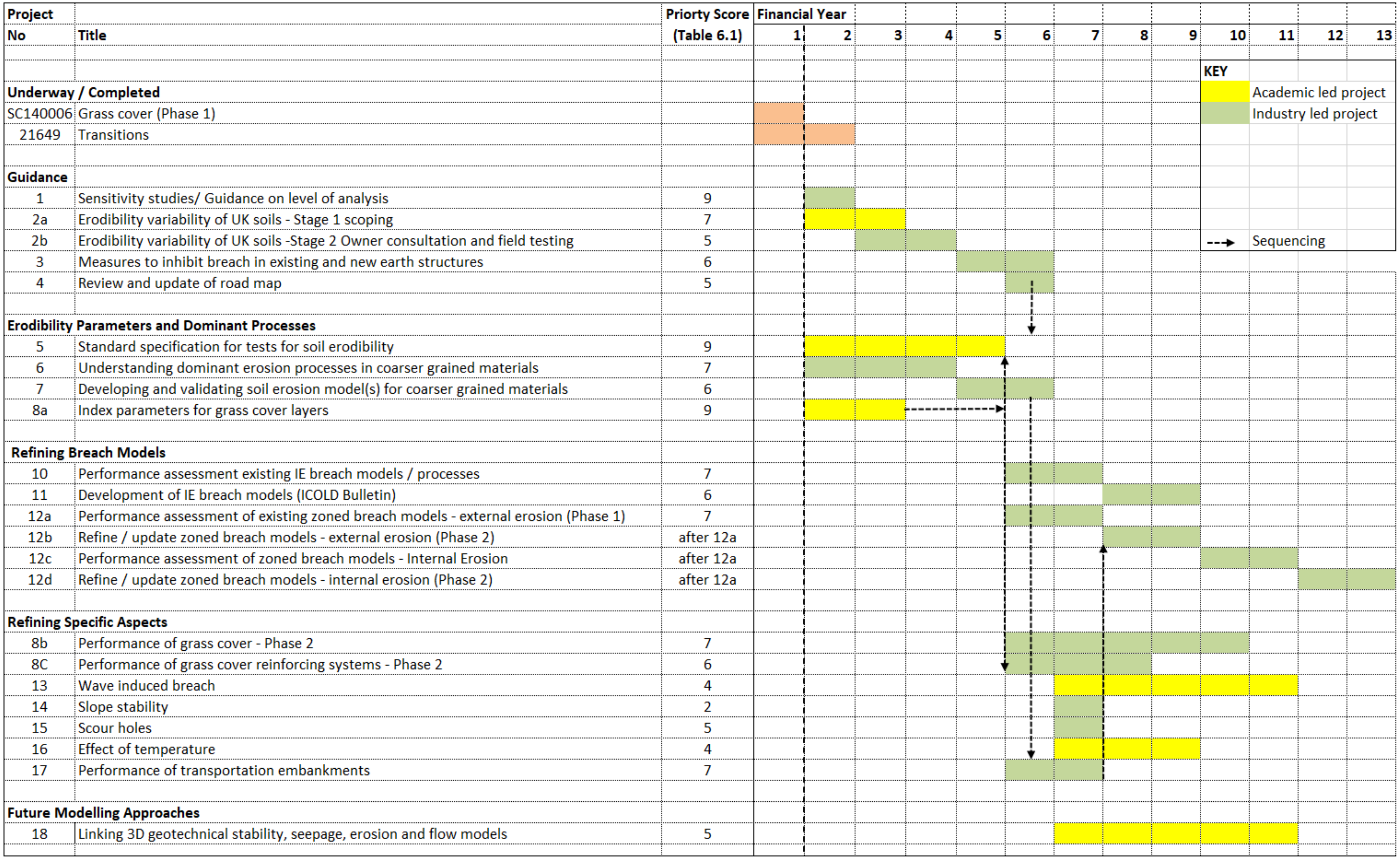


Figure 44 - Gantt chart showing the outline 10 year+ programme for breach research in England and Wales.

5.6.3. Procurement of projects

It is recognised that significant issues are to be addressed in delivering these projects. These include:

1. Opportunities to gain efficiencies by grouping projects.
2. Liaison with academia and encouraging a number of universities to develop research programmes in breach-related research.
3. Process and procedures to facilitate international collaboration.
4. Evaluation of fixed-price tenders:
    a. weighting given to scoring
    b. whether a group of specialists should be retained to advise on tender evaluation (as is done for European research), to ensure that tender claims regarding experience and competency are valid, and that the proposed methodology to deliver the required output is realistic.

Some of these may come within the scope of the Reservoir Safety Research Advisory Group (ReSRAG), but the responsibilities for others is indeterminate and needs addressing as part of implementing this plan.

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Appendix A: Defining breach initiation, formation and growth processes

A logical structure may be established by first considering breach in relation to the shape of the outflow hydrograph and secondly by behaviour (as defined by material type). These are outlined below and build upon work by Morris (Morris, Hanson and Vaskinn, 2006) and Visser (1998) on non-cohesive breaching, and Temple (Temple and others, 2005) for cohesive breaching.

The generic breach outflow hydrograph

Figure 45 below shows a typical flood hydrograph that might arise from breach through an embankment or dam. In practice, the detailed shape and duration of the hydrograph will be determined by the type of hydraulic loading (i.e. the volume of water retained behind the embankment; the variation in loading such as storm loading, tidal cycles etc) and the nature of the soil. The initiation flow (period T1 to T2) might also vary, for example, showing periodic surges where initiation was prompted by wave overtopping. However, the broad features demonstrated in this example are generally common to all breach hydrographs in varying degrees. The series of time markers indicate different stages of breach activity as explained below.

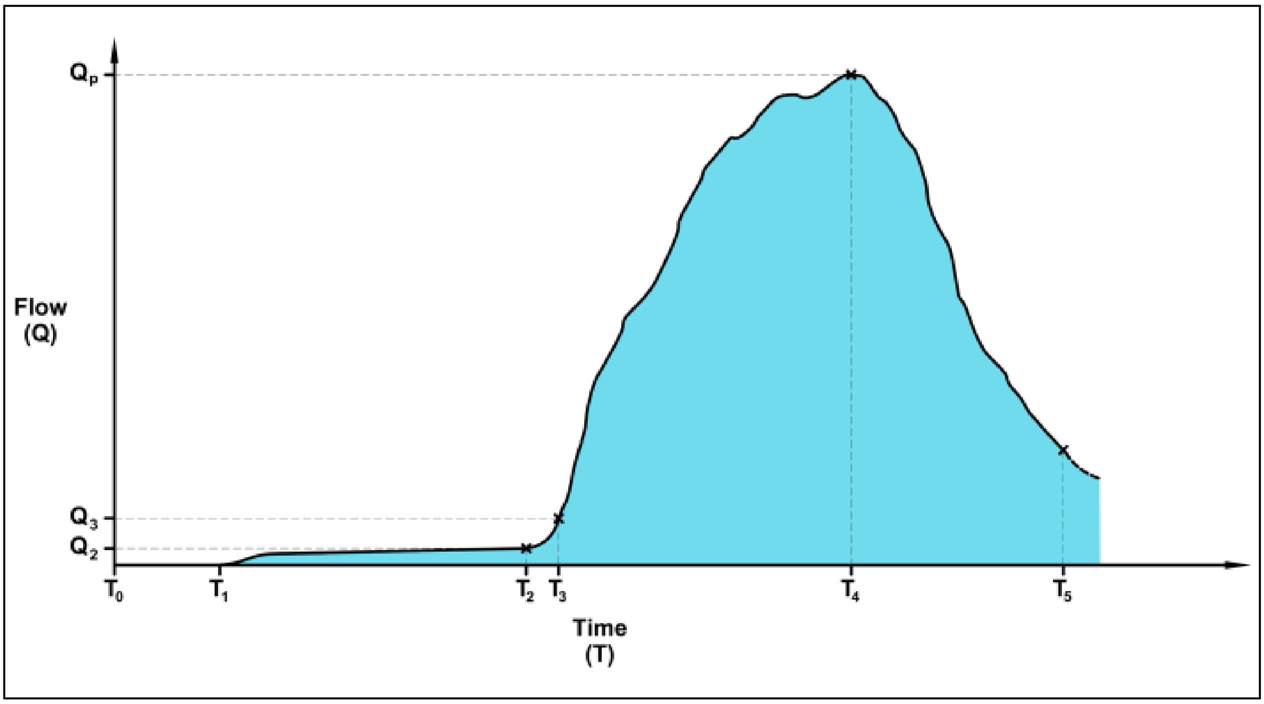

Figure 45 - Generic breach flood hydrograph

Table 13 provides a summary of each stage of the generic breaching process, including relevance to end user, indicators of the process and indicative current modelling ability. The writer's assessment of breach modelling ability is based upon conclusions found during the European IMPACT project (Morris and Hassan, 2005a), the more recent Dam

Safety Interest Group (DSIG) breach modelling project (Wahl et al, 2008; Wahl, 2009; Working Group et al, 2017) and judgement regarding modelling advances as identified through the literature review.

Table 13: Generic breaching process stages (Morris, Hanson and Hassan, 2008)

Time	**T0**
Process:	Stable – no breach initiation
Indicator:	None
Inspection methods:	Routine – non-specific
Relevance:	Flood embankment or dam is performing as intended
Current modelling capability:	Not required
Time	**T1**
Process:	Start of breach initiation; seepage through or over the embankment initiates
Indicator:	Damp patches on embankment; variations in vegetation growth; cloudy seepage water
Inspection methods:	Visual (seepage and vegetation); infra-red photometry; ground water temperature
Relevance:	It is important to identify the potential for breach before it actually occurs for effective asset management; seepage is often not visible and difficult to locate
Current modelling capability:	Limited; limit state equations exist for surface and internal erosion processes; a high degree of uncertainty exists in any prediction
Time	**T1–T2**
Process:	Progression of breach initiation; breach flow increases slowly through either or both increased loading and the progressive removal of material; flow is typically small, and the rate of change can be very slow; the time period may be hours, days or months
Indicator:	Apparent steady seepage or overtopping; cloudy seepage water; no signs of rapidly changing flow
Inspection methods:	As for T1; flow monitoring to detect change in flow rate
Relevance:	Having identified a potential problem, awareness of the timescale for development is often critical in determining the most appropriate action for maintenance, repair, emergency planning etc
Current modelling capability:	Poor; there is a high degree of uncertainty in both the process and time prediction

Time	T2–T3
Process:	Transition to breach formation; critical stage where steady (and relatively slow) erosion cuts through to the upstream face of the embankment initiating relatively rapid and often unstoppable breach growth; transition may occur within hours
Indicator:	Visibly changing flow conditions and quickening erosion of embankment through upstream face; cloudy seepage water
Inspection methods:	Monitoring seepage flow quantity and quality
Relevance:	Knowing when growth transitions to and past T2 is critical for emergency action
Current modelling capability:	Included in many models, although typically limited representation
Time	**T3–T5**
Process:	Breach formation; rapid erosion of embankment vertically; continued erosion of embankment vertically and laterally; extent and rate dependent upon volume of available floodwater and design and condition of embankment
Indicator:	Rapid breach growth; turbulent, sediment laden flow; continued widening of breach after initial formation
Relevance:	Important for predicting potential inundation downstream; lateral growth important for planning emergency repair works
Current modelling capability:	Prediction of hydrograph – moderate (peak ± 30% [IMPACT project (Morris, 2005]); ability to predict lateral growth rate and ultimate breach dimensions is poor
Time	**T4**
Process:	Peak discharge; Q_p is a function of available floodwater and embankment design and condition
Indicator:	Difficult to identify during rapidly varying conditions
Relevance:	Often used as a measure of worst case; however, Q_p at the breach does not necessarily relate to worst flood conditions downstream
Current modelling capability:	± 30% (most accurate of all aspects of breach modelling)

It should be recognised that Figure 45 and the summary of stages above provide a simplified summary. Different combinations of soil erodibility in relation to reservoir (flood) volume can result in significantly flatter and longer-duration flood hydrographs. It should also be recognised that this type of breach represents conditions where the flood outflow is affected by the breach size. In some situations, such as with canal breaches, where the canal channel is relatively narrow in relation to the breach width, the breach discharge is controlled by the canal cross section geometry and the pound-stored water volume. In this situation, the breach grows predominantly as a function of water flowing along and out of the canal; the breach does not control the outflow and the hydrograph tends to be flatter and prolonged, rather than rapid and peaky (Dun, 2007).

Appendix B: Candidate research projects

Project ref SC140006 - Performance of grass cover – Phase 1 scoping study

Predominant process External erosion

Soil Type All

Breach stage 1

Issue to solve

Predicting how grass cover will perform under different load conditions ranging from very low to very high overflow depths and durations.

Anticipated approach

Literature review and science-based case to establish the current state of knowledge and to develop a Phase 2 programme of research tests to address gaps in knowledge leading to the provision of tools to quantify loading at limit states of no damage and perforation of grass cover.

Type of project Scoping (desk)

Practical outputs

Clearly defined current state of knowledge.Considered review of current international approaches; combined with current state of knowledge to allow recommendations for way forward so as to improve practice.

Expected impacts and outcomes

Logical case and proposed steps for Phase 2 programme of research.

Relevant current research and dependency

SC140006 Grass and Soil Erosion Project.Should build from EC FloodProBe project work.

Scope in Appendix C

Project ref 21649 - Transitions

Predominant process External Erosion / Internal Erosion

Soil Type All

Breach stage

Issue to solve

Erosion typically initiates at transition points within a structure, whether on the structure surface, within the body or through the structure. The risks posed by different types of transition (and hence the processes that occur) are not methodically logged or understood.

Anticipated approach

To understand how transitions affect the performance of a structure, its susceptibility to erosion and potential failure. To

a) define a clear typology of different transitions that exist in levees and dams

b) provide a clear summary of potential erosion and failure processes that can occur with different transition types, and the risks these can pose to structure performance

b) develop methods for predicting the risk of erosion arising from different types of transition.

Type of project Desk study

Practical outputs

Industry guidance regarding the assessment of transition-related erosion and failure processes – identifying and providing solutions where known, and gaps in knowledge where not.

Expected impacts and outcomes

Better understanding of the risks posed by transitions, underpinning more focused asset inspection and risk analyses.

Relevant current research and dependency

Recent EA tender

Scope in Appendix C

Project ref 1 - Sensitivity studies, guidance on level of analysis and risk-based approaches

Predominant process External Erosion

Soil Type All

Breach stage All

Issue to solve

1. The extent of uncertainty in different breach prediction methods has not been quantified leading to subjective descriptions as to the value of different approaches.

2. Provide a guide for users for scoping the breach failure progress and the appropriate level of analysis.

3. Provide guidance on different risk-based approaches (rather than process based) that may also be used for breach prediction.

Anticipated approach

A rigorous assessment of uncertainty within methods would provide clarity and help assure appropriate use of different methods.

Carry out example analyses with different models and methods, for different scenarios, showing how the uncertainty in prediction varies between methods and models (including the effects of different soil erodibility and hydraulic load conditions).

Report(s) showing how each of the breach prediction methods perform for a range of different scenarios.

Quantification of uncertainty in method predictions for different scenarios.

Review and present options for how breach prediction can be expressed probabilistically such that system risk modelling can build upon the most up-to-date breach process modelling knowledge.

Type of project Desk study

Practical outputs

Demonstration of the typical magnitude of uncertainty – and the key sources of uncertainty – in using different methods of breach analysis.

Hence, guidance on uncertainty in different levels of analysis, and thus guidance on selection of the appropriate level of analysis for different end uses.

Guidance on the use of risk-based approaches (as well as process based approaches).

Expected impacts and outcomes

1. Greater clarity in understanding the potential range of breach outcomes with credible ranges of input variables (and breach prediction methods), and hence the relative importance of the different input parameters (and methods).

2. More appropriate selection of methods for predicting breach for different end uses.

3. Greater consistency in use of current knowledge between process and risk-based approaches.

Relevant current research and dependency

None identified.

Note: This is not a summer student project due to complexity of models and applications.

Scope in Appendix C

YES

Project ref 2a - Erodibility variability of UK soils – Stage 1 Scoping

Predominant process External erosion / Internal erosion

Soil Type All

Breach stage All

Issue to solve

Variations in soil erodibility in nature and from construction can result in weak areas with respect to erosion. However, it is unclear how big the variations can be, and how to assess them.

Anticipated approach

Investigating and understanding how natural variation and construction variability in soils can occur and to what extent. Provide recommendations as to the likely range of variability in the erodibility of any soil – natural or constructed. Consider potential variation in UK, and also on a worldwide basis, to understand how UK may vary from other countries.

Type of project Desk/lab/field

Practical outputs

Guidance/predictions as to how natural and constructed soil erodibility may vary in the UK.

Expected impacts and outcomes

Ability to integrate natural and constructed variability into performance models – whether stability analyses or breach analyses.This will allow for better representation of soil performance by stability and breach models.

Relevant current research and dependency

None identified Check USACE/USBR/USDA

Scope in Appendix C

YES

Project ref 2b - Erodibility variability of UK soils –Stage 2 Owner consultation and field testing

Predominant process External erosion

Soil Type All

Breach stage 1 to 3

Issue to solve

There is very little guidance available to estimate the likely erodibility of soils for UK dams and levees, and hence what values should be used in any breach/risk analyses.

Anticipated approach

Assess the range of erodibility of UK dams and levees by looking at the types and state of materials used in the UK. Consideration of how material state varies according to age, quality of construction, use, climate change etc. will be needed to allow for variations in erodibility from optimum. A report detailing:

(i) typical soil types found and used in the UK

(ii) typical erodibility values for such soils

(iii) likely variations from typical values caused by construction, maintenance, local conditions, climate effects etc.

Type of project Scoping and guide

Practical outputs

Validated guidance for industry use in preliminary breach analysis of typical erosion rates of soils in the UK.

Expected impacts and outcomes

This would allow an understanding of the potential range of breach hydrographs and allow an informed decision on whether more detailed analysis was worthwhile.

Relevant current research and dependency

Might build from or incorporate or replace work under Phase 2 of SC140006.

Scope in Appendix C

YES

Project ref 3 - Measures to inhibit breach in existing and new earth structures

Predominant process External erosion / Internal erosion

Soil Type All

Breach stage All

Issue to solve

What are the options for structural interventions (retrofitting) to reduce the likelihood of full breach and release of contained water?

Anticipated approach

Desk study and consultation.

Type of project

Guide

Practical outputs

Guide on options to inhibit breach.

Expected impacts and outcomes

Facilitate structural modifications to slow breach development in existing dams and levees.

Relevant current research and dependency

Work on internal erosion.

Scope in Appendix C

YES

Project ref 4 - Update 2018 scoping project

Predominant process Internal erosion? External erosion

Soil Type All

Breach stage All

Issue to solve

Update vison of research that would add value to UK Flood Risk Management, in the light of implementation of the priority projects.

Anticipated approach

After delivery of priority projects update review of knowledge and make recommendation as to priority project for next phase.

Type of project

Desk study

Practical outputs

Scoping report updated.

Expected impacts and outcomes

Inform decision on funding/delivery of research projects.

Relevant current research and dependency

Scope in Appendix C No

Project ref 5 - Standard specification for tests for soil erodibility

Predominant process All

Soil Type All

Breach stage All

Issue to solve

Various methods have been developed to test soil erodibility (eg HET, JET, EFA). In addition, the JET test has been expanded and shrunk to both a large-scale and mini-JET test. When different tests are applied to the same samples, different results are found. It is unclear whether the differences arise from the different flow and soil characteristics within the tests, or simply the equipment itself. A reliable method or methods are required for the analysis of soil erodibility.

Anticipated approach

Research is needed to compare the test methods, understand the differences, define relationships between the procedures and produce a definitive standard specification for lab and field testing of soil samples.

Also provide tools to allow correlation of data from different existing test methods.

Type of project

Lab/field

Practical outputs

A standard method of measuring erodibility in the lab and field, and/or the ability to cross-relate results from different (existing) methodologies.

Expected impacts and outcomes

This would give greater certainty in erosion model predictions and greater acceptance by industry of erosion calculations underpinning breach and flood risk predictions.

Relevant current research and dependency

EDF is currently exploring use of different sizes of JET test.

Scope in Appendix C

YES

Project ref 6 - Understanding the progression of surface erosion through the analysis of dominant soil erosion processes

Predominant process External erosion

Soil Type All

Breach stage 2–3

Issue to solve

Different soil types and grading erode in different ways (headcut, surface erosion, slump etc). The relationship between macro erosion processes and soil type, grading and state is also unclear, but can significantly affect the way in which a structure breaches. Research is needed to understand how the dominant erosion processes will vary in relation to soil type, grading and state.

Anticipated approach

Investigate the erodibility of different soil types, states and gradings in order to be able to understand how both macro and micro erosion processes vary in relation to soil type, grading and state.[Note that the focus here is to identify when and why macro processes change, and to better understand the erosion processes of fine and coarser-grained materials under breach conditions].Outputs likely to comprise technical reports leading to the definition of processes and erosion relationships that can then underpin industry guidance on erosion calculation.

Type of project

Desk, lab and field

Practical outputs

Definition of different types of soil macro erosion process and rate.

Confirmation of existing or development of new micro erosion relationships.

Expected impacts and outcomes

Significant step forward in ability to predict real (rather than broad/averaged) dominant erosion processes through dams and levees. Ability to differentiate type of macro erosion process and rate. Step improvement in the accuracy of erosion prediction (and hence flood risk management).

Relevant current research and dependency

EDF/ CNR/ HR Wallingford/ Polytech University of Madrid University are developing an international programme of work (spring 2018). This builds from the Aussois workshop discussions (Dec 2017). The programme is open to wider international (funded) collabo

Scope in Appendix C

YES

Project ref 7 - Developing and validating surface erosion model(s) for coarser-grained materials

Predominant process External erosion

Soil Type All

Breach stage 2–3

Issue to solve

Ensuring that validated, practical model(s) are available for industry use to apply the new knowledge gained in Phase 1 of the project into practice.

Anticipated approach

To provide independently validated breach model(s) which incorporate the new science from Phase 1 of the project.

The process would follow the approach used by the CEATI DSIG breach modelling project, whereby potential models and potential datasets are reviewed and chosen, and the performance of the selected models is tested, reviewed and agreed through international collaboration.

Report(s) explaining how the performance of different breach models/ methods compared and hence recommendations supporting industry use of the models.

Type of project Desk

Practical outputs

Production of new soil erosion model(s) or validation of existing soil erosion model(s).

Clear recommendations as to the validity of using new breach prediction models for specific applications.

Expected impacts and outcomes

Greater clarity and industry awareness as to the availability and applicability of breach erosion model(s).

More accurate breach prediction (flood risk analysis and management) arising from better models and wider application.

Relevant current research and dependency

This translates the new science solutions identified in Phase 1 of the project to industry validation of model(s) methods using the new science.

Scope in Appendix C

YES

Project ref 8a - Grass cover –Index parameters to allow comparison between sites

Predominant process External erosion

Soil Type All

Breach stage 1

Issue to solve

Defined by Phase 1 scoping study.

Anticipated approach

A programme of lab and field tests to define index parameters for both grass cover (sward) and root system, to allow comparison of grasses between different sites in terms of resistance to hydraulic surface loading. Would ideally include index parameters to define level of defects in grass systems, such as bare patches, animal holes etc.

Type of project Lab and field

Practical outputs

Develop new (separate) index parameters for grass sward and root system performance.

Expected impacts and outcomes

Would allow performance comparison between sites in terms of grass resistance to hydraulic loading.

Relevant current research and dependency

SC140006 (CH2M) Grass and Soil Erosion Project.

Should build from EC FloodProBe project work.

Scope in Appendix C

YES

Project ref 8b - Performance of grass cover - Phase 2 Lab and Field

Predominant process External erosion

Soil Type All

Breach stage 1

Issue to solve

Defined by Phase 1 scoping study.

Anticipated approach

A programme of lab and field tests to address gaps in knowledge regarding grass/soil performance in the UK. New guidance, superseding and extending beyond CIRIA 116, for the design and performance assessment of grass cover at limit states of no damage and perforation.

Type of project

Lab and field

Practical outputs

Industry guidance on grass performance, superseding CIRIA 116, addressing a wider range of flow conditions and using a more rigorous analysis approach.

Expected impacts and outcomes

More reliable design and performance method, reducing uncertainty in design and risk assessment.

Relevant current research and dependency

SC140006 (CH2M) Grass and Soil Erosion Project.

Should build from EC FloodProBe project work.

Scope in Appendix C

Output from Project 8a

Project ref 8c - Performance of grass cover – Phase 2 Reinforcing systems

Predominant process External erosion

Soil Type All

Breach stage 1

Issue to solve

Anticipated approach

Lab and field test data on the performance of different grass reinforcement systems, relating to conditions found in the UK. New guidance, superseding and extending beyond CIRIA 116, for the design and performance assessment of reinforced grass cover.

Type of project

Lab and field

Practical outputs

Industry guidance on reinforced grass performance, superseding CIRIA 116, addressing a wider range of flow conditions and using a more rigorous analysis approach.

Expected impacts and outcomes

More reliable design and performance method, reducing uncertainty in design and risk assessment.

Relevant current research and dependency

SC140006 (CH2M) Grass and Soil Erosion Project. Should build from EC FloodProBe project work.

Scope in Appendix C

Output from Project 8a

Project ref 9 - Understanding the progression of internal erosion from initiation through to breach formation

Predominant process Internal erosion

Soil Type All

Breach stage 1–3

Issue to solve

Predicting how different forms of internal erosion initiate and subsequently progress to the point where breach formation will occur.

Anticipated approach

Theoretical and laboratory analyses validated where possible against field observations.

Type of project

Desk and lab

Practical outputs

Initial models/ methodologies to allow prediction of the progression of IE from initiation to breach formation.

Expected impacts and outcomes

Allowing a potential timeframe to be attached to the development and progression of IE at a dam or levee.

Relevant current research and dependency

EPSRC research funding?

Scope in Appendix C

YES

Project ref 10 - Performance assessment existing IE breach models/ processes

Predominant process Internal erosion

Soil Type All

Breach stage 2–3

Issue to solve

Recent research has identified 4–5 different forms of internal erosion (ICOLD Bulletin 164 – 4 types; USACE/USBR adaptation of ICOLD – 5 types). These processes have typically not been integrated into breach models; most breach models only simulate part of the concentrated leak erosion process. International validation of models for predicting breach from internal erosion has not yet been undertaken. This is needed to provide industry with recognised tools/methods.

Anticipated approach

This initiative would: (i) identify and review existing models (the long list); (ii) critically review these models in terms of science and data to validate them, and identify a shortlist for stage 3; (iii) compare and validate the performance of selected existing prediction models; (iv) identify the adequacy of existing models to model all 4 stages of breach, or whether new models need to be developed to model Stages 2 to 4.

The objective here is to validate existing models for use by industry and/or define research needs for models appropriate to all breach stages. Report(s) explaining how the performance of different internal erosion breach models/methods compared and hence recommendations supporting industry use of the models.

Type of project Desk/lab

Practical outputs

Clear recommendations as to the validity of using existing internal erosion breach prediction models for specific applications.

Define any further research needed to develop models of internal erosion for Stages 2 to 4 of breach and for the various different IE mechanisms.

Expected impacts and outcomes

Greater clarity as to the availability and applicability of existing internal erosion models.

Relevant current research and dependency

EDF is seeking to establish a collaborative international effort to undertake this work (spring 2018). The process would be similar to that undertaken for the CEATI DSIG breach modelling project.

Scope in Appendix C

No

Project ref 11 - Development of IE breach models (ICOLD Bulletin)

Predominant process Internal erosion

Soil Type All

Breach stage 2–3

Issue to solve

Develop breach models for IE appropriate to mass wasting/gross enlargement of concentrated leaks through embankments. Separate models may be required for stoping/ concentrated leaks.

Anticipated approach

To be defined after Phase 1

Type of project

Desk/lab/field

Practical outputs

Industry model(s) for the prediction of IE based upon current state of knowledge.

Expected impacts and outcomes

Use of latest models and methods for predicting IE will result in better flood risk analysis and management.

Relevant current research and dependency

Scope in Appendix C

No

Project ref 12a - Performance assessment of existing zoned breach models – external erosion (Phase 1)

Predominant process External erosion

Soil Type All

Breach stage 3

Issue to solve

Zoned structures comprise different zones of soil type and/or soil state, resulting in zones of soil with differing erodibility. Breach models are typically based upon the erosion of simple homogeneous structures. The way in which breach formation occurs can be significantly affected by zones of material eroding in different ways and at different rates, so also affecting flood risk.

Anticipated approach

Review and validate breach models for the prediction of breach through zoned structures due to external erosion. The process would typically: (i) review existing models; (ii) review existing data; (iii) compare and validate the performance of existing prediction models. Dominant physical processes are likely to include erosion of downstream shoulder with loss of support to core, following by rigid block failure of core.

Type of project

Desk and lab

Practical outputs

Clear recommendations as to the validity of using existing zoned breach prediction models for specific applications.

Expected impacts and outcomes

Better understanding of availability and applicability of zoned breach models (better flood risk assessment…).

Relevant current research and dependency

Likely to benefit from links with international breach research (ie DSIG breach modelling project) including EDF, USBR, USACE etc.

Scope in Appendix C

No

Project ref 12b - Refine/update zoned breach models – external erosion (Phase 2)

Predominant process External erosion

Soil Type All

Breach stage 3

Issue to solve

Anticipated approach

Type of project

Practical outputs

Industry validated zoned breach model(s).

Expected impacts and outcomes

Improved flood risk analysis for breach through zoned structures.

Relevant current research and dependency

Likely to benefit from links with international breach research (ie DSIG breach modelling project) including EDF, USBR, USACE etc.

Scope in Appendix C

No

Project ref 12c - Performance assessment of zoned breach models – Internal erosion

Predominant process Internal erosion

Soil Type All

Breach stage 3

Issue to solve

Zoned structures comprise different zones of soil type and/or soil state, resulting in zones of soil with differing erodibility. Breach models are typically based upon the erosion of simple homogeneous structures. The way in which breach formation occurs can be significantly affected by zones of material eroding in different ways and at different rates, so also affecting flood risk.

Anticipated approach

Review and validate breach models for the prediction of breach through zoned structures due to internal erosion. The process would typically: (i) review existing models; (ii) review existing data; (iii) compare and validate the performance of existing prediction models. Dominant physical processes are likely to include creation of ‘holes through cores’, and the subsequent interaction with the shoulders, which may plug or filter material being eroded through the core.

Type of project Desk and lab

Practical outputs

Clear recommendations as to the validity of using existing zoned breach prediction models for specific applications.

Expected impacts and outcomes

Better understanding of availability and applicability of zoned breach models initiated by internal erosion (better flood risk assessment…).

Relevant current research and dependency

Likely to benefit from links with international breach research (ie DSIG breach modelling project) including EDF, USBR, USACE etc.

Scope in Appendix C

No

Project ref 12d - Refine/update zoned breach models – internal erosion (Phase 2)

Predominant process Internal erosion

Soil Type All

Breach stage 3

Issue to solve

Anticipated approach

Type of project

Practical outputs

Industry-validated zoned breach model(s) initiated by internal erosion.

Expected impacts and outcomes

Improved flood risk analysis for breach through zoned structures initiated by internal erosion.

Relevant current research and dependency

Likely to benefit from links with international breach research (ie DSIG breach modelling project) including EDF, USBR, USACE etc.

Scope in Appendix C

No

Project ref 13 - Wave-induced breach

Predominant process External erosion

Soil Type All

Breach stage 1

Issue to solve

Waves impact on the structure and surge turbulent flow across the crest and downstream in a cyclic process. Damage and erosion can occur to different parts of the structure in different ways/rates to that which occur from uniform overflow. A clear understanding of the wave-induced breach process (not just grass damage) is required. Eurotop2106 gives very different outcomes from floods and reservoir safety, e.g. no limit on overtopping for Hs(significant wave height)< 0.3, vs overtopping < 1 litre/s/m (which require a wave freeboard of > 0.6m for those of 0.2m). Engineering guidance needs to be updated to reflect the importance of wave height (and ratio to crest width).

Anticipated approach

To understand the difference in soil erosion and breach formation arising from both wave impact and overtopping or water overflowing through lab and field tests. If possible, define a) rate-dependent relationship for equivalence of loads from overtopping (waves) and overflow. b) relationship between wave loading and soil erosion rate. c) breach processes arising from the combination of wave impact and overtopping Consider range of waves applicable to both reservoirs and levees i.e. 0.1m to 2m.

Type of project Desk, lab and field

Practical outputs

A more precise model or method to predict erosion and breach arising from wave impact and overtopping.

Expected impacts and outcomes

This will allow the risks from wave action to be better quantified.

Relevant current research and dependency

Wave overtopping simulators provide information on the first stage of the breaching process. Wave impact/run-up simulators are now also under development (Infram) and will be useful in studying breach processes on different structures.

Scope in Appendix C No

Project ref 14 - Impact of slope instability on vulnerability to external erosion

Predominant process External erosion

Soil Type Fine-grained

Breach stage 1

Issue to solve

Breach can occur because a structure has slumped or failed due to instability, pore pressures etc so lowering the crest control. This followed by overflow or overtopping leading to breach. When slumps or failures occur, how does this affect the risk of breach occurring?

Anticipated approach

Understanding how slope or defence failure due to rapid drawdown/ overburden affects the risk of sudden breach formation. The aim is to consider how different structures may fail, and the implications of such failure for breach initiation in relation to flood loading. Some structure designs may be more susceptible to subsequent breach formation than others.

Processes to be defined in a format allowing fragility curve representation and predictive breach model simulation.

Type of project Desk

Practical outputs

Definition of the ways in which slope failures might arise and how they will initiate breach.

Expected impacts and outcomes

Allows inclusion of these processes into breach prediction models and representation within system risk analyses (fragility curve representation).

Relevant current research and dependency

TE2100 / TEAM2100 studies find this issue a particular problem.

Scope in Appendix C No

Project ref 15 - The effect of scour holes during breach

Predominant process External erosion

Soil Type All

Breach stage 3 & 4

Issue to solve

Scour holes can form within and downstream of a dam or levee breach. The conditions needed to create such holes have not been widely defined, and the effect on the breach formation process is not well understood. It is unclear whether inclusion of scour holes as part of breach prediction methods is important or not.

Anticipated approach

To confirm whether scour holes significantly affect breach prediction results or not. Both physical processes and model prediction impacts should be investigated to determine the need for this process to be included or not. Where significance is proven, to determine appropriate methods for inclusion within breach prediction models.

Type of project Desk/lab

Practical outputs

Breach prediction model(s) including the effects of scour holes within the prediction method(s).

Expected impacts and outcomes

Improved representation (accuracy) of predicting breach processes supporting better flood risk analyses and emergency response.

Relevant current research and dependency

None identified.

Scope in Appendix C

No

Project ref 16 - Effect of temperature on seepage, soil erodibility and vulnerability to internal erosion

Predominant process Internal erosion

Soil Type All

Breach stage 1–3

Issue to solve

Some studies have indicated a relationship between temperature variations and seepage rates, soil erodibility etc. This adds additional uncertainty to the breach prediction process, and may be a further impact of climate change.

Anticipated approach

Scoping study into the effect of temperate on seepage, soil erodibility and stress distributions within embankments (and thus vulnerability to initiation of IE).

Type of project

Scoping and lab PhD?

Practical outputs

Improved knowledge and model(s) relating changes in soil erodibility to changes in temperature.

Expected impacts and outcomes

Better ability of industry to assess drivers that may lead to initiation of seepage and also affect the rates of erosion. (ie more effective risk assessment and management.)

Relevant current research and dependency

None identified. Could be a PhD?

Scope in Appendix C

No

Project ref 17 - Performance of transport embankments

Predominant process Internal erosion / External erosion

Soil Type All

Breach stage All

Issue to solve

Transport embankments (road, railway etc) are typically not designed to retain water yet are placed across floodplains and in flood risk areas where they can act to retain water. It is unclear how such embankments would behave under high flood conditions.

Anticipated approach

(i) Develop a clear understanding of the type and state of materials that may be found in difference transport embankments; (ii) provide guidance on the likely erodibility of such materials.

Type of project

Desk/lab /field

Practical outputs

Improved knowledge and guidance on how transport embankments respond under flood conditions and how to represent this within breach prediction model(s).

Expected impacts and outcomes

Allows for more realistic (validated) breach assessment of transport embankments within flood risk analysis models.

Relevant current research and dependency

Links to other infrastructure management organisations (road, rail etc).

Scope in Appendix C

No

Project ref 18 - Linking geotechnical stability and breach formation process models

Predominant process Internal erosion / external erosion

Soil Type

Breach stage

Issue to solve

At present, dam and levee stability may be analysed in 2D/3D and seepage behaviour may be analysed in 2D/3D. However, while such models may predict instability and the onset of failure, they do not predict the breach formation process. Breach models predict breach formation but starting from the assumption of seepage or overflow/ overtopping. The development of integrated models that can undertake both would provide a more reliable overall prediction.

Anticipated approach

The challenge is to integrate models (in 2D and/or 3D) combining multiple different processes (eg open flow, closed flow, internal seepage, soil deformation, soil erosion, soil cracking, block failure, mass wasting). This will allow prediction of all processes from initial erosion through seepage or overflow to open breach.

Type of project Potentially PhD

Practical outputs

Next-generation breach model(s) including more detailed and fully integrated 2D/3D analyses of physical processes affecting the performance of dams and levees during breach formation.

Expected impacts and outcomes

Improved modelling representation of structure performance underpinning more accurate flood risk analyses.

Relevant current research and dependency

There have been some academic studies that partly solve this challenge using ever more complex 2D and 3D modelling platforms. Hence, this is achievable, but currently in academic sphere.

Scope in Appendix C No

Appendix C: Outline scope for proposed priority projects

Contents

1 - Sensitivity studies, guidance on level of analysis and risk-based approaches

Context

There is currently a lack of appreciation among asset owners of factors affecting the potential breach discharge, information required to estimate this, or the potential uncertainty in output from different methods. This leads to inappropriate use of breach methods – or no use at all.

Industry guidance is required to demonstrate the differences between approaches, the different levels of uncertainty in predictions from different approaches and how this can affect applications.

Overall objectives/issues to solve

Produce a guide for engineering professionals managing water-retaining assets to allow them to scope the potential breach failure processes and understand the options for predicting breach hydrographs and the uncertainties involved in the different approaches. This would include the following:

1. Undertake analyses considering different asset types, hydraulic load conditions and soil parameters (including erodibility) using at least 3 different methods for predicting breach for each case. Comparison of predicted outcomes, including flood hydrograph characteristics, peak discharge, timing and sensitivity to variations in the modelling parameters should be undertaken to allow a clearer understanding of what additional information each method provides, and what degree of uncertainty may be present in the predictions. Results should be validated through comparison with published data on breach formation.
2. Review and present options for how breach prediction can be expressed probabilistically such that system risk modelling can build upon the most up-to-date breach process modelling knowledge.
3. Provide guidance (building on this 2018 breach scoping report) on how the stages of breach develop, how the different prediction methods quantify this, the degree of uncertainty present in each approach and the implications for subsequent applications.

Scope/methodology

- Stage 1 requires careful, objective analyses, with a key step being agreement on the sample assets, loads conditions and tools to be used.
- Making a meaningful interpretation and summary of the output from the initial analyses is critical. In particular, recognising which aspects of the results are driven by the breach prediction methods and which by the test conditions.
- Validation using published data on breach formation would ideally be carried out in partnership with organisation(s) that have already collated such validation data.

- Stage 2 requires knowledge of breach formation processes, probabilistic approaches and system risk modelling approaches.
- Stage 4 should be written by someone familiar with current methods of breach analysis.

Specific outputs

- Engineering guide to modelling breach
- Supporting volume with results of the sensitivity studies

Expected impacts and outcomes

- One step towards delivering the vision that:
- "the engineering professions and others involved in managing water-retaining assets will have a better and more consistent understanding of breach processes and be applying these in their management of all forms of built infrastructure."

Indicative budget

Low

Indicative duration

4 months

Likely nature of research

Desk based

Tangible deliverables

- Data
- Research report (New Science)
- Engineering guidance

2a (Soil erodibility 1) - Erodibility of UK dams and levees – desk analyses

Context

In the geotechnical field there are various CIRIA and other reports that publish typical geotechnical properties for specific geological strata (see Table 17.8 of RARS (Environment Agency 2013a, 2013b), and Appendix B of Reeves, Sims and Cripps, 2006). This provides awareness of potential ranges of parameters for preliminary screening assessment and assists in scoping site-specific ground investigation.

However, there is no comprehensive review/guide of the erodibility of UK soils that could be used to support breach analysis and scoping site-specific testing.

Overall objectives/issues to solve

1. Provide a summary of UK soils likely to have been used in the construction of dams and levees based on geological origin, and the likely range of erodibility parameters for each soil type (GIS overlay of asset locations onto geology).
2. Provide a correlation between geotechnical index parameters, and erodibility coefficients used in computer models of breach (build on Appendix C of Guide to drawdown capacity [Environment Agency, 2017]).
3. Collect and summarise published data on the erodibility of soils, both internationally and in UK.
4. Suggest typical erodibility parameters both in situ (in the foundation), and when used as fill (remoulded) for common UK soils. The latter should:
   a) take into account the range of construction techniques likely to have been used, depending on date of construction, purpose and developer
   b) include suggested uncertainty/potential variability.
5. Comment on whether maintenance regime and/or climatic change could affect these parameters, and if so, how.
6. Use this to comment on:
   a) where research priorities should be in UK if governed by predominant soil types
   b) how UK soils vary from international soils (noting effect of climatic differences on weathering processes), and implications for when international research would be relevant to UK conditions.

Scope/methodology

Limited to desk-based study, and international/UK consultation.

Specific outputs

A guide to the erodibility of UK soils, for use in preliminary screening assessment of breach, and scoping site-specific investigations.

Expected impacts and outcomes

One step towards delivering the vision that:

“the engineering professions and others involved in managing water-retaining assets will have a better and more consistent understanding of breach processes and be applying these in their management of all forms of built infrastructure.”

Better understanding of where soils are likely to be erosion-resistant and further breach analysis is a lower priority, and sites where soils are likely to be of higher erodibility so further investigations/assessment should be a priority.

Indicative budget

Medium

Indicative duration

1 to 2 years

Likely nature of research

Desk based; perhaps an MSc or part of a PhD

Tangible deliverables

- Data
- Research report (New Science)
- Engineering guidance

2b (Soil erodibility 2) - Erodibility of UK dams and levees – owner consultation and field testing

Context

As 2a

Overall objectives/issues to solve

Extend scoping stage (2a) by obtaining field data on UK dams and levees:

a) obtaining factual and interpretative reports from asset owners
b) designing and carrying out ground investigation at, say, 6 sites
c) ensuring above include a range of hole erosion and/or jet erosion tests on both in situ fill and fill near optimum moisture content (OMC) compacted to modern standards (lowest practicable erodibility).

Invest in some site-specific testing as ‘pump priming’ to encourage major asset owners to carry out testing on their own assets.

Scope/methodology

Initial desk study to collate selected data where data is relevant to the spread of erodibility of UK soils.

Prior to any fieldwork, the 6 sites should be selected to best reflect the range of conditions found in the UK. This selection (of structure type and location) will be based upon findings from the preliminary work (9a).

At each site the relevance of undertaking either or both hole and jet erosion tests will be agreed, and the number of samples appropriate for the site.

Soil samples will be taken, and erosion analyses performed in the laboratory.

Specific outputs

1. Research report on findings from 6 sites.
2. Supplement to Stage 1 report with any changes in recommended ranges in parameters for breach analyses.

Expected impacts and outcomes

As 2a, but with improved reliability (through the provision of 6 example site analyses covering different structures and locations across the UK).

Indicative budget

Medium

Indicative duration

2 years

Likely nature of research

Field sampling and laboratory analyses

Tangible deliverables

- Data
- Engineering guidance

3 - Measures to inhibit breach in existing and new earth structures

Context

Research into breach should not only consider the effects of breach (Do Nothing), but also options to reduce the likelihood of breach. This should cover both the use of surface reinforcement systems, and other potential structural measures to inhibit or delay breach, eg clay cover layer, sheet piles, filters.

Without this guidance many of the benefits of research into breach would not be realised, as improved modelling of breach simply provides refined estimates of consequences for the Do-Nothing scenario, but does not facilitate positive intervention through structural modifications.

Overall objectives/issues to solve

Produce guidance on options to inhibit breach of existing and new dam embankments and levees due to both internal and external erosion. To include case studies and information sufficient to allow users to assess viability of options at their dam. It is accepted that research into breach will improve our knowledge of the base processes, and thus this would be produced now as an interim guide, aiming to update and issue as a definitive guide, say, 10 years after issue of the interim guide.

This project includes measures to inhibit breach:

a) due to both external and internal erosion
b) at transitions (this aspect not currently funded [but may subsequently be funded] by the separate research project awarded 2018)

Scope/methodology

It is anticipated that this would be limited to a desk study and consultation both in the UK and internationally, and that the report would not repeat existing guidance, but would simply provide a concise summary and pointers to these references.

Specific outputs

Interim guide to measures to inhibit breach of embankment dams and levees, to include:

- concise summary of breach processes
- description of structural modifications that can be taken to slow or prevent breach development, including information required to assess viability and effectiveness

Expected impacts and outcomes

Improved understanding of factors governing time to failure (breach with release of the retained water), and measures that could be taken to prolong this time and inhibit full development of breach.

Indicative budget

Low

Indicative duration

One year

Likely nature of research

Desk study and consultation

Tangible deliverables

- Engineering guidance

5 (Soil erodibility 3) - Standard specification for soil erodibility

Context

Various methods have been developed to test soil erodibility (eg HET, JET, EFA). In addition, the JET test has been expanded and shrunk to both a large-scale and mini-JET test. When different tests are applied to the same samples, different results are found. It is unclear whether the differences arise from the different flow and soil characteristics within the tests, scale effects of surface tension, etc, or simply the equipment itself.

EDF are currently examining the effect of different sizes of JET test, and previously funded one PhD to investigate the issues (Regazzoni, 2009).

Overall objectives/issues to solve

Develop standard internationally accepted test procedures, method or methods for the determination of soil erodibility, which would cover both cohesive and granular soils, and ideally would be linked to:

- erodibility index geotechnical tests
- parameters used in breach modelling software.

Scope/methodology

1. Scoping – identify existing ongoing work in this area and where fresh research would make a significant contribution to developing an international standard for defining and measuring soil erodibility.
2. Investigate the different soil erodibility measurement methods and how test results are analysed.
3. Identify how and why differences arise in erodibility measurement between the different approaches/equipment.
4. Develop an approach that allows for the measurement of soil erodibility – either through new test equipment, or by identifying how measurements undertaken by existing equipment may be cross-related. In doing so, it may also be appropriate to show how different existing items of equipment measure different erosion processes/soil behaviour, and hence the differences observed between erodibility results.

Specific outputs

1. Research report with results of research and lab testing on different test methods/apparatus to cover both cohesive and granular soils.
2. Proposed standard method of measuring erodibility in the lab and field, and/or the ability to cross-relate results from different (existing) methodologies.

Expected impacts and outcomes

Standard test method would provide more confidence in use of erodibility values and hence in:

a) breach models input and output
b) asset owners investing in testing of erodibility of soils present in their assets

Indicative budget

High – Academic-led

Indicative duration

4 years (2 PhDs, second starting after 1 year; 1 on cohesive soils, the second on granular)

Likely nature of research

Mainly desk- and lab-based

Tangible deliverables

- Data
- Research report (scoping)
- Research report (New Science)
- Model/tools
- Engineering guidance

6 (Soil erodibility 5) - Understanding the progression of surface erosion through the analysis of dominant soil erosion processes

Context

Different soil types and soil grading erode in different ways (headcut, surface erosion, slump etc). The relationship between macro erosion processes and soil type, grading and state, and stage of erosion is also unclear, but can significantly affect the way in which a structure breaches. Research is needed to understand how the dominant erosion processes will vary in relation to soil type, grading and state and stage of breach. This then allows for the most appropriate model(s) to be used when predicting breach formation. Research has already been undertaken investigating cohesive (silts, clays etc) behaviour in the form of headcut, but not for coarser-grained materials.

Overall objectives/issues to solve

The issues to solve are:

a) determine when and why macro erosion processes change from headcut to surface erosion, to slumping of coarse porous material
b) confirm the most appropriate particle erosion relationship(s) as grain size coarsens from clay and silts through to gravels.

In addressing these issues, care will be needed to establish the impact of fines (ie soil grading) on the overall performance of a sample and the stage of breach. Understanding of behaviour is sought for both clean and well-graded samples – as would be found in practice.

The research should take into account the common types of fill in UK dams and levees.

Scope/methodology

Medium- to large-scale laboratory and field research is required to investigate and understand soil erosion behaviour at both the micro and macro scales. The investigation is likely to include:

a) fine to coarse graded soil erosion behaviour at a macro scale (in order to confirm and identify when macro processes change from headcut to surface erosion to slumping)
b) soil erosion behaviour at a micro scale for a range of soil types to determine the validity of existing erosion relationships, or to support the development of new relationships
c) the effects of soil grading on soil erodibility, and subsequently upon micro and macro erosion behaviour.

The importance of this research has already been recognised by organisations such as USACE, USBR, USDA and industry companies such as EDF. USACE is currently undertaking some preliminary research at Vicksburg; EDF is developing a collaborative programme of work based in Europe, but intended to align with parallel efforts in the US. The most cost-effective solution for this work is some form of international collaboration.

Specific outputs

Specific outputs will include:

a) research data and report(s) detailing a programme of field and laboratory testing in order to understand micro and macro erosion behaviour as soil type varies from clay and silts through to gravels, and also stages of breach
b) research data and report(s) detailing a programme of field and laboratory testing in order to understand how micro and macro erosion behaviour is affected by the fines content in a granular soil, ie progressively changing from a clean material to a graded material
c) implications for breach prediction report, summarising the findings from the research (a and b above) and how this affects soil behaviour during the different stages of breach formation.

Expected impacts and outcomes

This research will provide a clearer understanding of how erosion processes vary according to soil type and grading. If appropriate, new erosion relationships will be defined for specific soil types and conditions. This new science will allow for the refinement and improvement of breach models – particularly for soil conditions that are coarser than clays and silts (ie for surface erosion-type failures rather than headcut-type failures).

It is noted that the scope of the project will depend on the degree of international collaboration.

Indicative budget

High if a standalone UK project.

However, see note above regarding the opportunity for international collaboration, such that it is suggested that a medium budget is allowed.

Indicative duration

3–4 years

Likely nature of research

Large-scale field; Medium/large-scale laboratory

Tangible deliverables

- Data
- Research report (scoping)

- Research report (New Science)
- Engineering guidance

7 (Soil erodibility 6) - Developing and validating complementary soil erosion model(s) for coarser-grained materials

Context

As for No. 5 above.

Overall objectives/issues to solve

The overall objective here is to translate the research findings from No. 5 above into a usable, validated breach prediction tool for industry use.

Scope/methodology

The process followed would be similar to the CEATI DSIG breach modelling group, whereby the performance of existing and newly developed models is compared and validated through international collaboration. The goal here is to objectively assess performance and agree on specific model(s) with potential for industry use. The steps are likely to include:

a) review and agreement of models/methods to be compared
b) review and agreement of test cases (from No. 5) and case study data sets for model performance evaluation
c) blind and aware group application of models to different data sets
d) group review and assessment of model performance
e) overall conclusions and performance validation.

As with No. 5, the most cost-effective solution for this work is some form of international collaboration, building from the research programme No. 5.

Specific outputs

Recommended model(s) for the prediction of breach processes through coarser-grained materials – in particular for surface erosion processes.

Expected impacts and outcomes

Clarity as to which models should be applied to which soil types and conditions – hence improved accuracy of prediction and more appropriate use of both new and existing models.

Indicative budget

Medium – however, see note in No. 5 regarding the opportunity for international collaboration.

Indicative duration

2 years

Likely nature of research

Desk-based (recommended international cooperation)

Tangible deliverables

- Data
- Model/tools
- Engineering guidance

8a (Soil erodibility 4) - Index parameters for grass cover layers

Context

Grass is used as surface reinforcement of both dams and levees, both to resist overflow and wave overtopping, and to facilitate surveillance for indicators of geotechnical distress.

Scoping project SC140006 has identified that there is no common basis on which to compare the resistance of different types of vegetation/grass to external erosion. Important factors include climate, plant type(s), subsoil and maintenance regime. This means current maintenance regimes are subjective, and the design of grass waterways (both plain and reinforced grass) has to rely on relatively dated guidance produced in 1987 (CIRIA Report 116, 1987).

Overall objectives/issues to solve

Develop a method and test index parameters which allow:

a) comparison of performance of (unreinforced) surface vegetation to external erosion, with parameters for both the sward (vegetation above ground) and root system, the latter taking into account the subsoil (granular or cohesive)
b) assessment of defects in the cover layer, such as bare patches (eg moles, rabbits, desire line footpaths), variability of plant type etc
c) parameters to be applicable to performance of grass up to initial damage, ie loss of surface cover over 25% of the surface.

Comment on whether the parameters could apply to cover layers reinforced with geotextiles/open concrete blocks, and if not, what research would be needed for this extension.

Scope/methodology

It is anticipated that this will be carried out by a combination of literature review and desk studies, perhaps with some limited laboratory testing. More substantial laboratory or field tests might be undertaken as part of a Phase II programme of work for the Scoping project SC140006.

Key aspects will be to understand how different organisations (in particular the Dutch and US) have assessed grass performance, whether any particular existing approach is best and whether a new approach might be better.

Specific outputs

1. Technical report with definition of recommended index parameters, methods of measurement and recommended actions needed to validate the approach.
2. Research report providing evidence for basis of proposed parameters, probably as one summary report supported by separate reports on individual research projects.

Expected impacts and outcomes

Improved understanding of what features of the cover layer (eg sward length, root density, soil type) provide most resistance to external erosion, and thus supporting:

a) improved design and maintenance of grass waterways
b) recommendations supporting aspects of SC140006 Phase II
c) informed decision on achieving balance between engineering and ecological drivers in maintenance of grass cover to earth embankments
d) tools for comparison between different sites, both in terms of:
    - vulnerability of existing grass-covered banks to scour
    - linking research projects.

Indicative budget

Medium

Indicative duration

1-2years (MSc)

Likely nature of research

Academic-led

Tangible deliverables

- Data
- Research report (New Science)
- Engineering guidance

9 (Soil erodibility 7) - Understanding the progression of internal erosion from initiation through to breach formation

Context

ICOLD Bulletin 164 (ICOLD, 2013) identifies different internal erosion processes and conditions for each process to occur. However, currently no methods are available to predict the progression of these processes from initiation through to breach formation. Such methods are necessary to understand the potential timescale for erosion development and hence the risks posed to the dam or levee.

Overall objectives/issues to solve

The issues to solve are:

a) confirm the conditions needed to initiate different internal erosion processes (starting from the current guidance given in ICOLD Bulletin 164 (ICOLD, 2013) and USBR Risk management: Best practices and risk methodology Chapter IV-4)
b) develop basic erosion models to allow prediction of the potential progression of each erosion process through time.

The research should take into account the common types of fill in UK dams and levees and cover the range of erosion progression from first initiation through to breach formation. Note that once internal erosion results in collapse of the dam or levee 'roof' this becomes an open breach problem, which is currently addressed by other models and/or research actions that this initiative should not duplicate.

Scope/methodology

This research is envisaged to be an academic initiative undertaken through desk and laboratory analyses and supported with some form of numerical model development and analyses.

Specific outputs

Specific outputs will include:

- research data and report(s) detailing a programme of desk and laboratory analyses into the understanding of different internal erosion processes and their prediction.

Expected impacts and outcomes

This research will provide a clearer understanding of how internal erosion processes initiate and progress to failure for different types of soil and hydraulic load conditions. (This is important to realistically model peak breach flow due to internal erosion.)

Academic models of different processes are envisaged as part of this research.

Indicative budget

Medium–high

Indicative duration

4 years

Likely nature of research

Desk and laboratory tests

Tangible deliverables

- Data
- Research report (scoping)
- Research report (New Science)

Appendix D: Information in support of future developments

Indicative annual cost of maintaining and building new UK dams and levees

The potential benefits of breach research to the UK have been valued as potential annual savings in the cost of maintenance of existing assets, and construction of new assts.

The annual cost of operating and maintaining UK dams has been estimated as shown in Table 14. Firstly, reservoir safety managers at 3 major dam owners have provided overall costs of all of their dams, typically over a 10-year period, broken down into the headings shown in table. For this report only the average cost per dam is shown, to maintain anonymity. These have been taken as the average cost of a large dam, following the international definition for a large dam. The precautionary capital cost is the mandatory works recommended in the periodic Reservoir Act Section 10 safety inspections.

The cost of other dams coming under UK legislation, but not large as defined by ICOLD, have been taken as 25% of this value.

The number of dams in each category is the number in England, provided by the Environment Agency Reservoir Safety Section in Exeter.

Table 14: Indicative annual average cost of maintaining a dam in England

	Large Dams (Number=312)					Other UK dams (Number=1685)		
	Cost £k/year/dam				Cost £m	SWA Estimate	Say 25% of large dam	Cost £m
Owner number	1	2	3	Adopted for study			USE THIS	
Surveillance	£11.6	£9.7	£14.7	£12.0	£3.7	£4.0	£3.0	£5.06
Maintenance	£3.4	£29.0	£13.1	£15.0	£4.7	£2.0	£3.8	£6.32
Management	£3.4	£6.5	£4.9	£5.0	£1.6	Ind in surev	£1.3	£2.11
Emergency Planning	£0.4	£3.2	£3.3	£1.0	£0.3	£0.1	£0.3	£0.42
Capital Works – made good breach								
Capital Spend – precautionary	£82.1	£51.6	£45.8	£65.0	£20.3	£5.0	£16.3	£27.38
TOTAL	£100.7	£100.0	£81.7	£98.0	£30.6	£11.1	£24.5	£41.28

Table summary: This table shows the indicative costs of maintaining a dam in England. Costs are split by size of dam (large or other), type of expenditure and by Owner Number, and given in thousands of pounds per year per dam. These costs are then multiplied by the number of dams in each category (large and small) to give total amounts. The figures show that the total costs for large dams, of which there are 312, are £30.6m, while the total costs for the 1685 other dams are £41.28m.

When the annual cost of maintaining a dam is combined with the number of dams, this results in the total annual average costs shown in Table 15. The equivalent values for levees are derived as shown in the notes to the table.

Table 15: Indicative annual cost of dams and levees in England

	International Large dams (typically water supply reservoirs)	Dams coming under UK legislation, but not large as defined by ICOLD	Total	Fluvial and Coastal Levees (Note 2)	Total Levees and Dams
Number of existing assets in England and Wales	312	1685	1997	9000km	
Number built in the last ten years	None	171	171		
Number of properties at risk from flooding (million)			1.0	2.4	3.4
Average annual costs of existing assets £1m					
Surveillance/monitoring	£3.7	£5.1	£10.6	£0.4	£11
Maintenance	£4.7	£6.3	£10.6	£21.1	£32
Management	£1.6	£2.1	£4.0	Included above	£4
Emergency planning	£0.3	£0.4	£0.4	£64.5	£65
Capital spend – repair after breaches	£0.0	£0.0	£0.4	£0.6	£1
Capital spend – precautionary	£20.3	£27.4	£42.7	£387	£430
Annual average on existing assets Total £m	£30.6	£41.3	£68.3	£473.6	£542
Annual average capex invested in new assets £m (Note 4)			£17.0	£387	£404
Total existing and new build			£85	£860	£945

Notes

1. High level indicative estimate based on information from a number of water company dam safety managers, and authors' estimate of typical value for small reservoirs as shown in Table 14.
2. Currently not subdivided into embankment vs other forms of constructions
3. Costs for levees taken from annual investment need in long-term investment scenarios (published 2014 and updated 2019), assuming investment need is split 0.05% on surveillance, 2.5% on maintenance, 7.5% on emergency planning/forecasting, 45% on major repairs and 45% on new flood defences. Costs on repairs based on 22 repairs between 2007 and 2018, with an average repair cost of £280k.
4. Assume £1m average for new dams (majority farm reservoirs and flood storage reservoirs)

Table summary – this table shows the total annual average costs for maintaining dams and levees in England. It gives the annual average on existing assets as £68.3m for dams and £473.6m for fluvial and coastal levees, giving a total of £542m for all assets combined. The amount invested in new assets is £17m for dams, £387m for fluvial and coastal levees giving a total of £404m spent on new assets. The combined totals for existing and new build assets are therefore £85m for dams and £860m for fluvial and coastal levees, giving a total of £945m overall.

Indicative annual risk to life from UK dams and levees

Table 16 below makes an indicative order-of-magnitude estimate of:

a) the annual risk to life in England from dams and levees (83,500 potential deaths if all failed at once, equivalent to an average life loss of 16 lives/year)
b) the scale of capital investment that would be proportionate if it halved the probability of failure (£1.8 billion)

The calculations are intended to provide a possible order-of-magnitude estimate of risk to life from UK levees and dams, and what scale of capital investment would be proportionate to reduce this risk. These values are used in the business case in Chapter 5. The calculations they are based on are further explained in Table 16 and its supporting text. It is acknowledged that some benefits are time relevant and may not be immediately recognised.

It is important to recognise that the potential for all structures to fail at the same time (a) is extremely unlikely. For continuously updated estimates of the potential risk to life refer to the reservoir flood maps at https://www.gov.uk/guidance/reservoir-flood-maps-when-and-how-to-use-them.

Table 16: Indicative annual risk to life from dams and levees in England

Parameters	Comment	Units	Dams >15m (large)	Dams <15m	Source	Levees value	Levees Source	Total
Numbers of structures		Num	500	1500	BRE1994, consistent with Figure 1 of Deakin et al 2016	9000km	AMS p13	
Total number of people at risk from “breach” of structures	Average/ structure	Num people	2,000	200	Notes 2,3			
Total number of properties at risk			560,000	170,000	PAR divided by 1.8	1,000,000	AMS p13	1,730,000
Total population at risk (PAR).- time averaged		Num people	1,000,000	300,000	Num of dams x PAR per dam	1,800,000	2.35 people/ property and 80% average occupancy (=1.8) as RARS Table 9.2	3,100,000
Average fatality rate in event of breach			7%	2%	Notes 2,3	0.5%	Assume depth x velocity=1 $m^3/s/m$, and use RARS Figure 9.1 (see Note 4)	
Potential fatalities if all structures failed			70,000	4,500	PAR x fatality rate	9,000		83,500
Annual probability of failure			8.0E-05	4.0E-04	Notes 2,3	1.0E-03	See Note 5	

Parameters	Comment	Units	Dams >15m (large)	Dams <15m	Source	Levees value	Levees Source	Total
Overall (societal) life loss as annual risk		Lives/year	5.6	1.8	Number of fatality x probability of failure	9.0		16.4
Individual risk			5.6E-06	6.0E-06	Fatality rate x probability of failure	5.0E-06		
Value to prevent a fatality (VPF)	RARS Section 10.3	£m	£1.7	£1.7		£1.7		
Proportion factor (PF)	RARS Section 10.3		10	3		1		
Proportionate cost of one-off investment if would halve probability of failure (see Note 1)		£m	£1,428	£138	See Note 6	£230		£1,795

AMS – Asset Management Strategy 2017-2022

RARS – Guide to risk assessment for reservoir safety management. Report SC090001

Notes:

1. The international definition of a large dam is one which is over 15m high
2. Values of PAR, fatality rate and probability of failure for large dams are median from task 3 of FD2641, reproduced as Figure 48 and 49 and shown in RARS Figure 15,3 respectively. These values are consistent with values for Groups A to D in Brown et al 2008

3. Values of above for dams less than 15m high are more difficult to estimate, and have been obtained as follows:
    a. For consequence two estimates are available, the smaller dams in the data in FD2641, and Dataset E in Brown et al, 2008. A median value is used as shown in Table 20.
    b. For probability of failure 5 times more likely than large dams based on Figure 53 (which is in turn six times less than levees)
4. It is noted that the relationship between fatality rate and floodwater depth and velocity in Environment Agency Research Report FD2321 (2006) gives higher fatality rates than Figure 9.1 of RARS. This was noted in Brown et al (2012). It is considered that the RARS relationship is more applicable to the higher depths and eclarites associated with breach.
5. This assumes that most levees are designed for a 1in 100 chance per year storm, and the chance of failure if such a storm occurred is 10%. This annual probability of 1 in 1000 is of the same order as the plots on Figure 1 of Brown et al (2008)
6. This uses the equation in Section 10.3 of RARS, where the project costs to reduce risk to life is proportionate when *scheme cost ≤ VPF x PF x present value of saving (reduction) in probability of life loss* and assumes that over a 100 year investment horizon the present value is 30 times annual average life loss value.

Table Summary – This table shows how the risks of the consequences of dam failure have been calculated, both for large dams (over 15m in height) and other dams and levees. It details the figures used to calculate population at risk (PAR), value to prevent a fatality (VPF), and proportion factor (PF), as well as showing from where the figures were sourced. It shows that the estimated loss of life if all structures failed is 83,500, which combined with the probability of failure gives an annual risk of loss of life of 16.4 lives per year. The table goes on to show the costs involved in halving this risk as being £1,795m.

Table 20: Consequences of failure of UK dams < 15 m high (not large dams under international definition)

	>15m	<15m - FD2641	<15m - Brown et al 2008	Adopted
Median height		<10	5	
PAR	2,000 – Figure 48	700? – Figure 50	40 – Inferred from below	200
FR	7% - Figure 48	2% - Figure 51	1% - Fig 5 shows vd = 1.5m^3/s/m at 1km downstream	1.50%
LLOL	140 – RARS Figure 15.3	14 – Figure 52	0.4 – Figure 3 of 2008 paper	3

Table summary – This table shows how the consequences of failure were estimated for UK dams. It gives figures for PAR, FR and LLOL drawn from Figure 46 and RARS Figure 15.3 for large dams, and two figures drawn from FD2641 and Brown et al (2008) for dams under 15m in height. For these dams, a median figure was adopted as shown in the adopted column.

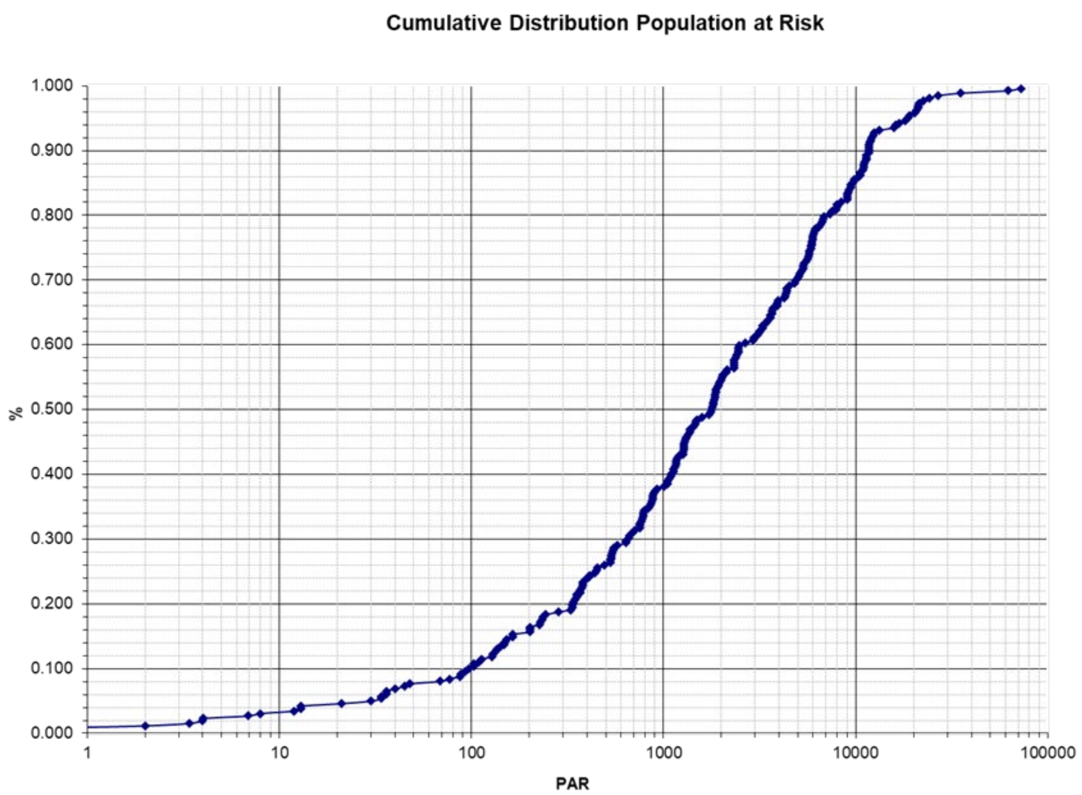

Figure 46 - Graph showing Data from FD2641 task 3 for sample of larger UK dams.

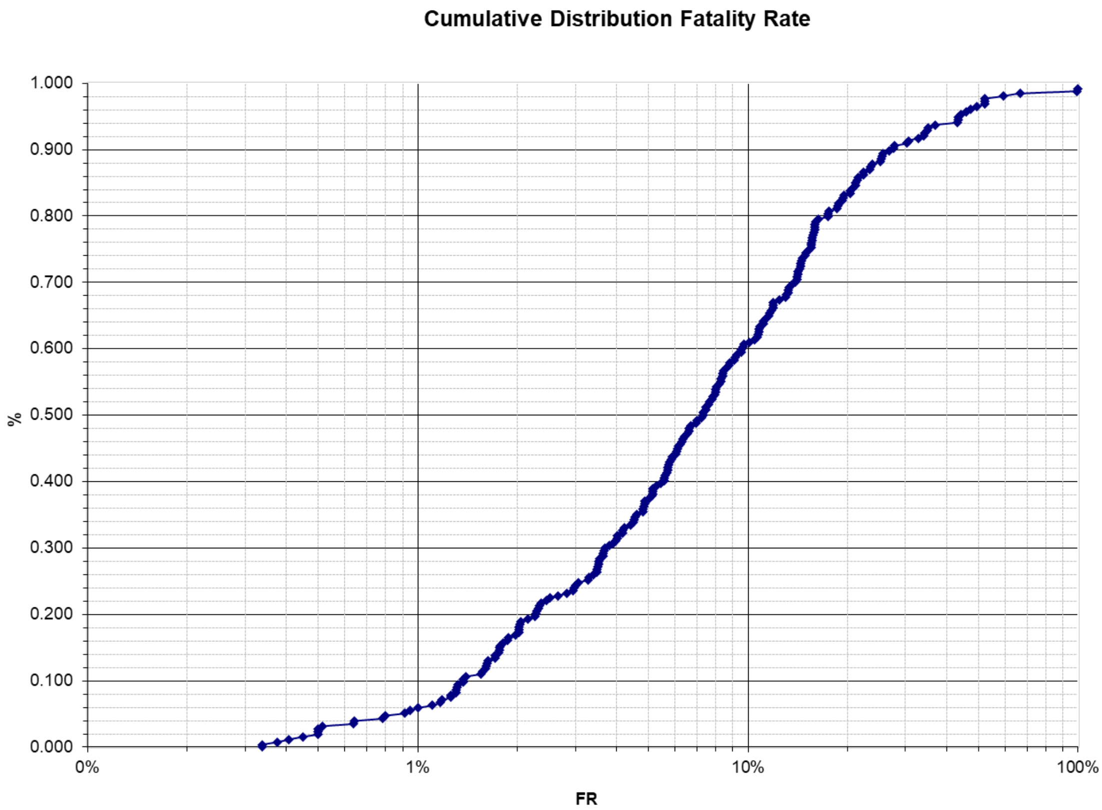

Figure 47 - Graph showing data from FD2641 task 3 for sample of larger UK dams

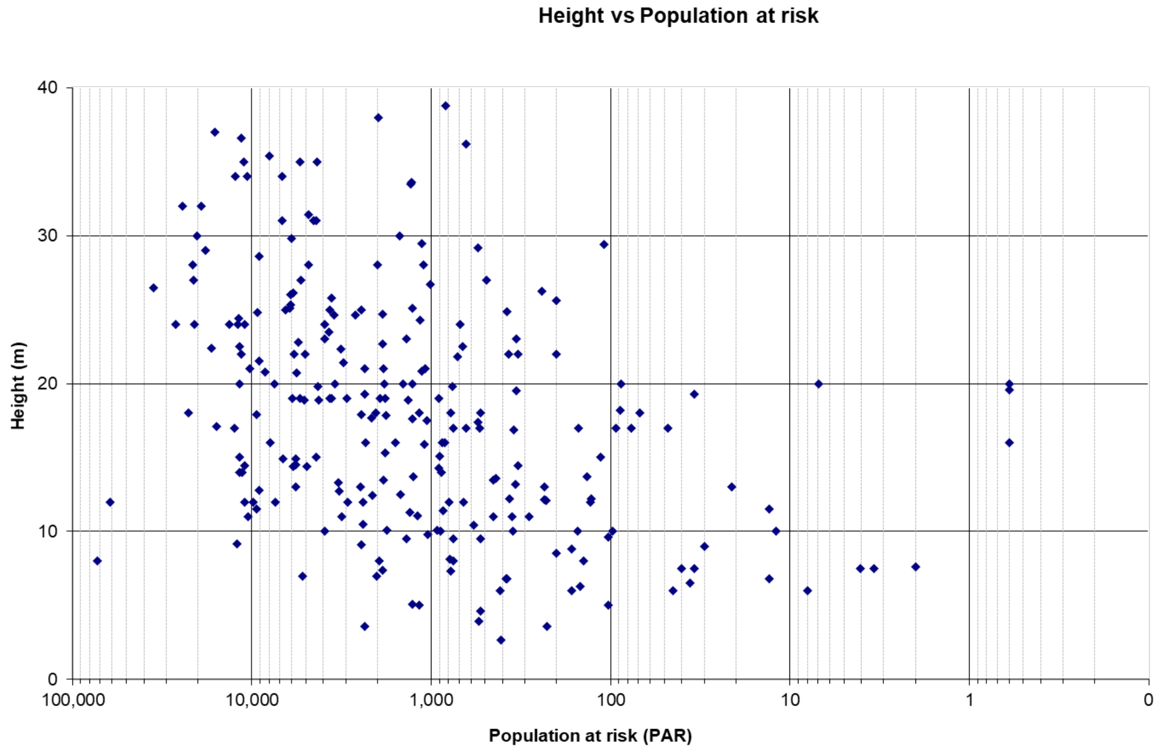

Figure 48 - Scatter graph showing data from FD2641 task 3 for sample of larger UK dams

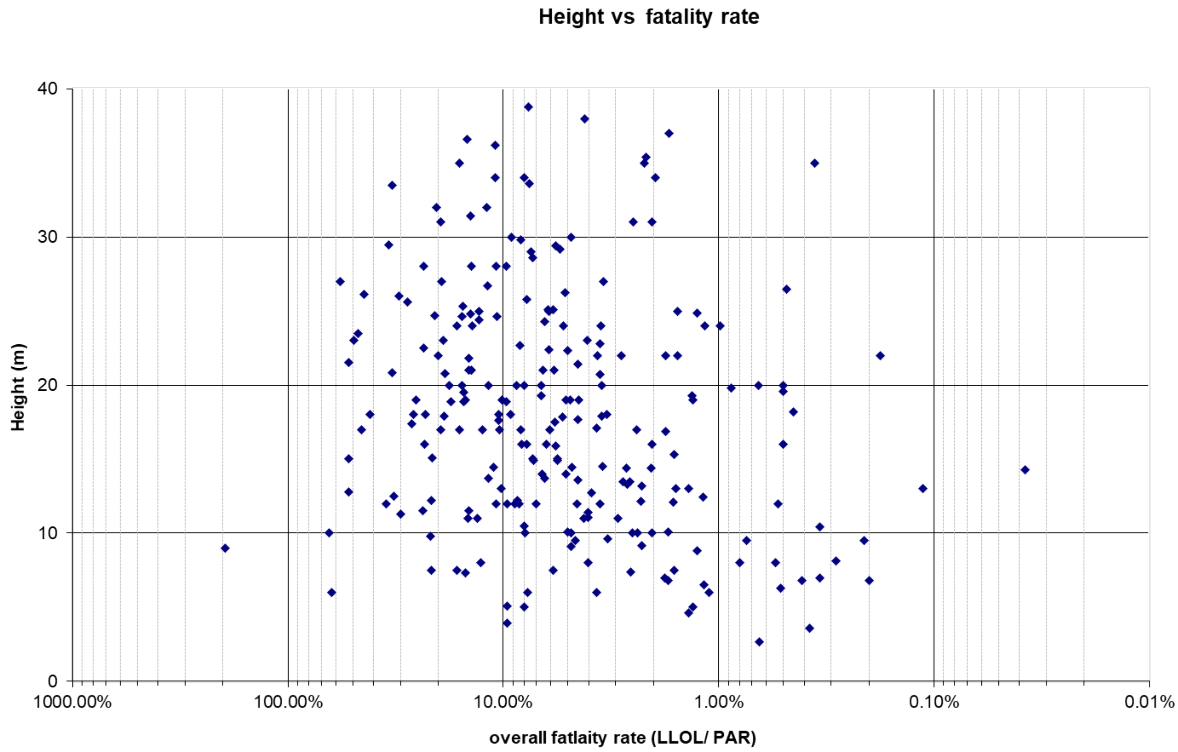

Figure 49 - Scatter graph showing data from FD2641 task 3 for sample of larger UK dams

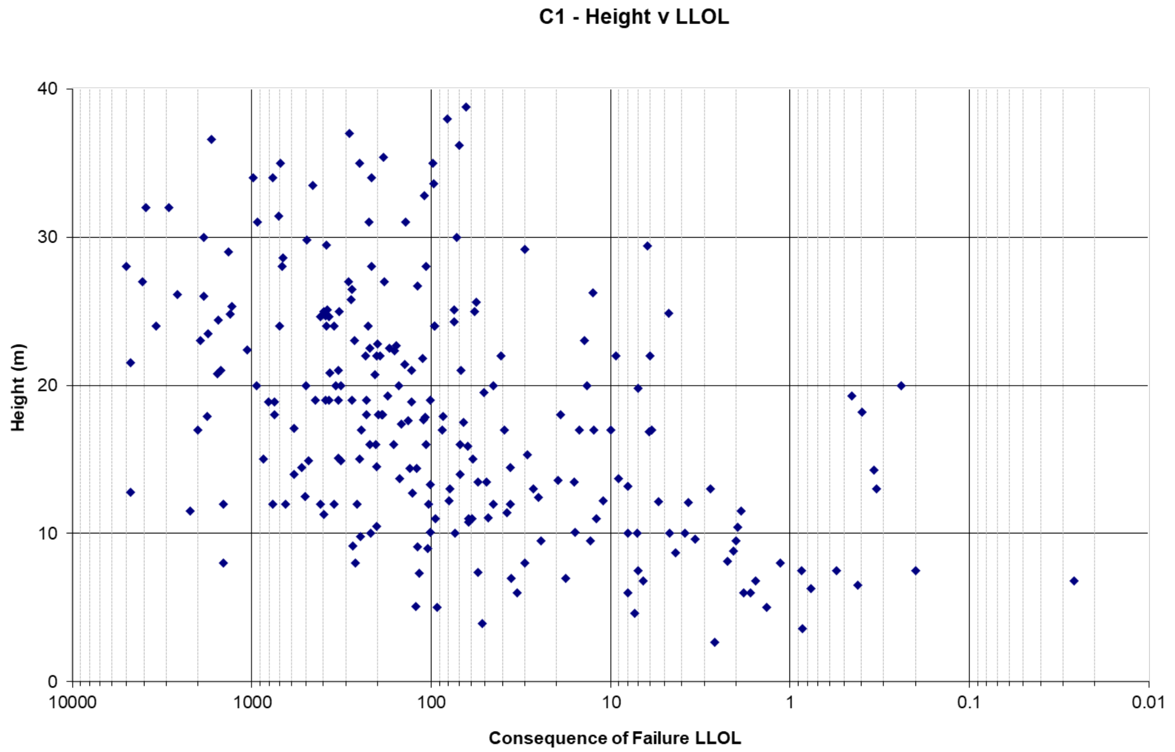

Figure 50 - Scatter graph showing data from FD2641 task 3 for sample of larger UK dams

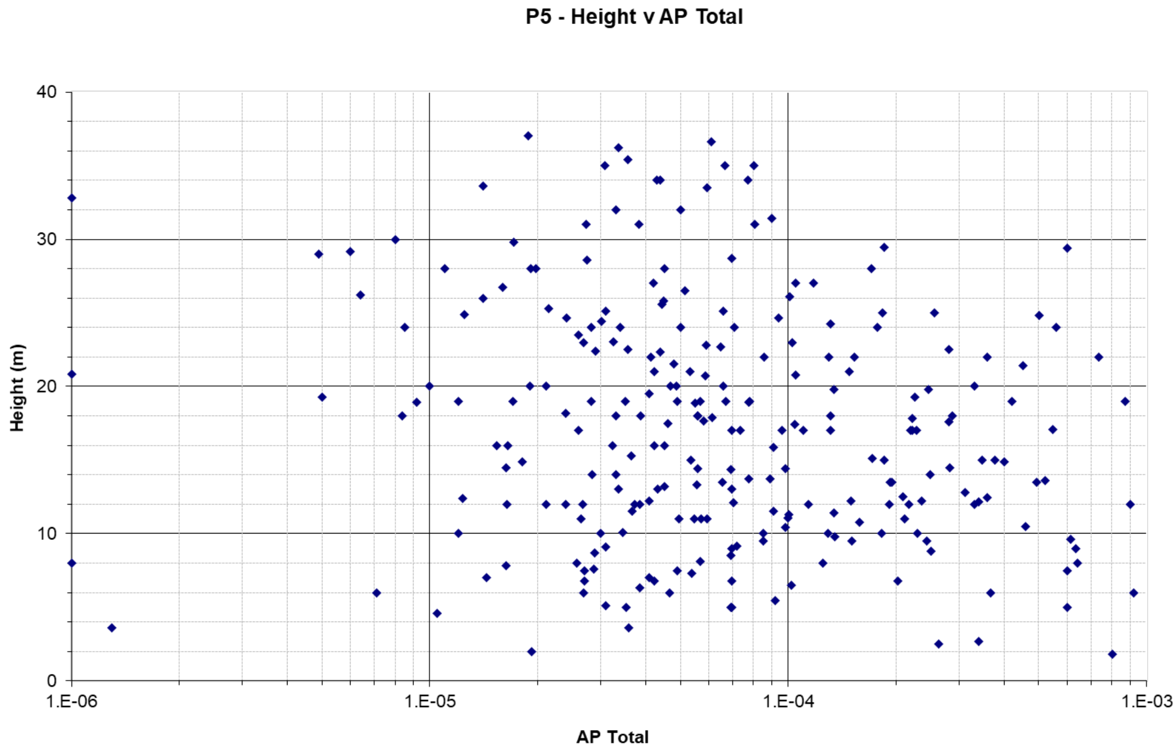

Figure 51 - Scatter graph showing data from FD2641 task 3 for sample of larger UK dams (AP = Annual Probability of failure)

The case for UK laboratory testing facilities

In recognising the importance of understanding and measuring soil erodibility, the question of who and how arises. Regardless of which technique or techniques may be used to measure erodibility (ie JET, HET, EFA etc), the process requires samples of soil to be tested under controlled conditions using equipment built to create specific conditions.

The prediction of soil erodibility may also appear relevant for answering other questions, such as field erosion from rainfall runoff and river bed and river bank erosion. However, processes such as river bed erosion and surface runoff occur under very different hydraulic and soil conditions. River bank erosion, where flow may erode and undercut banks, does, however, have similarities to breach erosion processes and its prediction would benefit from improved knowledge and measurement of soil erodibility as proposed here.

The various techniques that have been developed for soil erodibility measurement have arisen through researchers studying flow and erosion processes and then trying to replicate these conditions through laboratory test conditions. Hence, for example, for internal erosion, the HET was developed, for headcut erosion, the JET was developed and for more uniform surface erosion the EFA device was developed. Other variations also exist. Erosion functions have subsequently been developed relating to the use of one or other of these specific test equipment.

The current challenge is that there is no direct correlation of results between the different test results, making it difficult to transfer parameters from one form of measurement to another for use in specific, different erosion prediction models. It is proposed to address this issue under research action No. 5 (Appendices B and C).

Regardless of measurement technique, use of soil erodibility to improve predictions of dam and levee performance would create a demand for measurement services. At present, there are no established commercial laboratories in the UK offering this service. Small business services to meet this need are starting elsewhere in Europe – for example at Geophy Consult in France – see: http://geophyconsult.com/services/jet_en.html . In the US, federal agencies such as USDA or USBR can be approached to provide analyses.

While the creation of a facility to perform such tests may not be cost-effective for an individual asset manager, it could become a cost-effective small business at a national scale as either an independent newly created SME, an extension of an existing European business, or a business spinoff created with access to university laboratory facilities.

The size of the potential market in the UK is shown in Table 21. This would be a specialist test, similar to triaxial and other geotechnical tests, which tend only to be carried out at the larger soils laboratories. An estimate of the potential cost of a soil erosion test has been made as follows:

a) Examination on the internet of typical process for a drained triaxial test suggest it could be approximated as £150 for 4 days, plus £26/day giving, say, of the order of £300 + VAT for a 10-day test.
b) GeophyConsult (France) standard rate for JET tests in March 2019 are approximately €850/test if the sample is undisturbed, and €900/test if the sample is disturbed (more expensive due to time for sample preparation: water content, compaction), with a reduction of ~€50/test where there are 5 or more tests to perform. This is equivalent to, say, £725 + VAT per test.

Both examples exclude collection and transport of samples, reporting other than the basic test etc.

For a commercial laboratory to develop this facility they would need to invest in, purchase or build the test equipment, allocate space in a laboratory and train technicians.

At the potential order of magnitude of commercial prices given above, the annual revenue could be of the order of £60,000 to £125,000 per year. At this level of annual income with a profit margin of, say, 20% the payback period on the initial investment for a commercial laboratory to add this test to their capability is likely to be 5 to 10 years, and they would need a commitment of funding for a sustained test programme.

Table 21: Potential size of the market for commercial soil erodibility test facilities

Feature	Dam	levees		Total
Number of potential sites	1997	3,000	say every 3km	
Percentage of sites tested	30%	10%		
Number of sites/ year (see Note 1)	20	10		0
Number of tests/ site	6	5		
Number of tests/ year	120	50		170
Assumptions				
1. Complete population of dams and levees tested once over 30 years				

Appendices References

BRE,1994. Register of British dams

Brown, Yarwood, King and Gosden, 2008. Application of the interim guide to QRA across multiple dam owners by multiple Jacobs offices

- Only reference to split out small dams from large dams (under international definition)

Deakin and others, 2016. Updating the English reservoir flood maps. Proc. BDS Conf. pp15–28

- (Figure 1 is update on BRE 1994)

Environment Agency, 2010. FD2641 – Scoping the process for determining acceptable levels of risk in reservoir design.

- Final report online. Data on range of characteristics of UK dams taken from unpolished Task 3 stage report. Figures 15.2 to 115.4 of RARS use the same source. The dataset is a sample of 350 reservoir, mainly water company and so biased towards larger UK dams

List of abbreviations

ALARP	As low as reasonably practical
ANCOLD	Australian National Committee on Large Dams
BEP	backward erosion piping
CAPEX	capital expenditure
cm3/N-s	cubic centimetres per Newton-second
DSIG	Dam Safety Interest Group
DSO	Dam Safety Office
dv	dependent variable
EE	external erosion
GIS	geographic information system
HEC-RAS	Hydrologic Engineering Centre-River Analysis System
HERU	Hydraulic Engineering Research Unit
ICOLD	International Commission on Large Dams
IE	internal erosion
Kd	soil erodibility
LLOL	likely loss of life
M	metre
m/s	metres per second
m3/s	cubic metres per second
MPM	material point method
NaFRA	National Flood Risk Assessment
OPEX	operating expenditure
Pa	pascal
QRA	Quantitative Risk Assessment
RAFT	Risk Assessment Field Took
RARS	risk assessment for reservoir safety
τ	effective sheer stress

τc	critical sheer stress
UNSW	University of New South Wales
USACE	US Army Corps of Engineers
USBR	US Bureau of Reclamation
USDA-ARS	US Department of Agriculture Agricultural Research Service
USDI-BR	US Department of the Interior Bureau of Reclamation

Glossary

Drawdown capacity

The capability (rate at which) a reservoir water level can be lowered in an emergency

EFA test

Erosion Function Apparatus – for determining soil erodibility (typically surface erosion conditions)

HET test

hole erosion test – for determining soil erodibility (typically for internal erosion conditions)

JET test

jet erosion test – for determining soil erodibility (typically for headcut erosion conditions)

For a more detailed glossary of terms related to flood risk and dams and levees, the reader is referred to the International Levee Handbook (CIRIA, 2013).

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0800 807060 **(24 hours)**

floodline

0345 988 1188 **(24 hours)**

Find out about call charges (https://www.gov.uk/call-charges)

Environment first

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