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Asset performance tools: improving defence performance curves using local knowledge – methodology

Report – SC140005/R3

Flood and Coastal Erosion Risk Management Research and Development Programme

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Professor Doug Wilson
Director, Research, Analysis and Evaluation

Executive summary

Introduction

The aim of the Asset Performance Tools programme is to develop practical and user-focused methods, tools and guidance to support flood and coastal erosion asset management. The programme focuses on the tactical elements of asset management: inspection, performance assessment and planning.

This report is concerned with raised defences. It describes a method for using local knowledge to develop asset-specific fragility curves (which describe the chance of breach as a function of loading level) and deterioration curves (which describe how asset condition is expected to change over time), building on existing sets of generic curves. Key challenges are to:

- enable users to supply their knowledge in their own language
- find the appropriate 'tier' for the method, that is, for what proportion of assets is it intended compared with the 'basic tier' of using generic curves and the 'more detailed tier' of advanced asset-specific analysis

The initial approach developed by the project team was tested by a group of asset managers, who confirmed the need for and usability of the proposed approach. The method was the basis within Phase 3 of the Asset Performance Tools project for the development of the Custom Fragility Curve tool and improvements to the existing Asset Whole Life Cost tool developed under an earlier project (SC060078).

Fragility curves

The study identified 7 relevant types of information that may be available to local asset managers. This finding was validated by testing on 3 case studies.

As outlined below, there are 3 potential ways in which these different types of information could inform fragility curves.

Where it concerns limited variations on the assumptions behind the generic curves, the information could be used to calibrate the appropriate generic curve by shifting, reshaping or interpolation. This is the case for event information, design information, hybrid asset types, more precise condition grade and local irregularities.

Where it concerns cases in which assets are not covered well by the existing curves, interpolation is not possible and the development of additional generic curves is required. These could then form the basis for local calibration again. This would only be worthwhile if such cases are relatively prevalent. This could be relevant for different asset sub-types, dominant failure modes, asset characteristics, dominant deterioration modes and typical irregularities;

Finally, some types of local information are not suitable for the pragmatic Custom Fragility tool but would be valuable for advanced asset-specific analysis.

Step 1 of the recommended implementation process concerns the interpolation between existing curves as used in the Custom Fragility Curve tool (see appendix). Step 2 is to add functionality to shift and reshape generic curves. Step 3 requires more significant work, developing new generic curves for prevalent cases not yet covered by the existing curves.

Deterioration curves

The study identifies 3 relevant information types that may be available with local asset managers, validated by case study testing. The analysis indicated that these could inform deterioration curves as follows:

- Historic condition grade trend: reshape existing curves
- Asset-specific information on type, maintenance, environmental exposure, quality of materials: interpolate between existing curves (similar to the Custom Fragility Curve tool for fragility curves)
- Overall assessment of residual life: enable user to define new curves (or parts of curves)

These 3 approaches are complementary and so it is recommended that they are all implemented. The first process has been implemented in the Whole Life Cost tool as part of this project (see final project report SC140005/R1).

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1.1 Asset Performance Tools Phase 3

Flood events over recent years have tested a large proportion of the UK's flood and coastal assets. As a result of this intensive flood period, increasing investment is needed to maintain assets at an appropriate standard. This is compounded by pressure on maintenance budgets. To enable the effective prioritisation of current and future investment in the Flood and Coastal Risk Management (FCRM) asset base, asset managers need to be able to assess the likely performance of individual assets in their current and improved states, as well as understanding this performance within the context of the asset system. To achieve the highest possible reduction in the number of people, properties, infrastructure and land at risk with the limited budgets available, it is important that flood and coastal investment is directed toward those assets where the biggest risk reduction can be made for the money available. In addition, the benefits of investing in these assets must be articulated quantitatively and transparently in order to support the case for investment.

The Asset Performance Tools project will help to achieve the recommendations from the National Audit Office and the Pitt Review relating to improved asset management and better asset data sharing between risk management authorities. The project also supports developments under the Environment Agency's Asset Information Management System (AIMS) and the Creating Asset Management Capacity (CAMC) programme.

This is the final part of this phased research programme on asset performance tools, building on previous research in earlier phases and the tools and research generated in the Performance-based Asset Management System (PAMS) project.

Phase 1 of the Asset Performance Tools (AP Tools) project developed the concept of a propeller framework to support asset management decision-making. This has been slightly revised since (Figure 1.1). Each arm of the propeller represents an element of tactical asset management: inspection, performance and risk assessment and planning, with information management at its heart. Each arm consists of tiers, reflecting the need to use simple approaches where possible, but also more complex approaches where needed, typically for more critical assets.

Phase 2 developed tools to support the condition inspection arm of the propeller framework.

Phase 3 focused on the remaining propeller arms, providing the tools and guidance required to:

- assess performance and risk
- support planning and investment decisions

Work in Phase 3 also sought to develop and integrate all of the propeller arms as one clear usable framework (Figure 1.1).

The guidance will assist all risk management authorities (including the Environment Agency, Internal Drainage Boards and local authorities) in their fluvial and coastal asset management by providing guidance on the level of detail needed for inspection, assessment and investment planning.

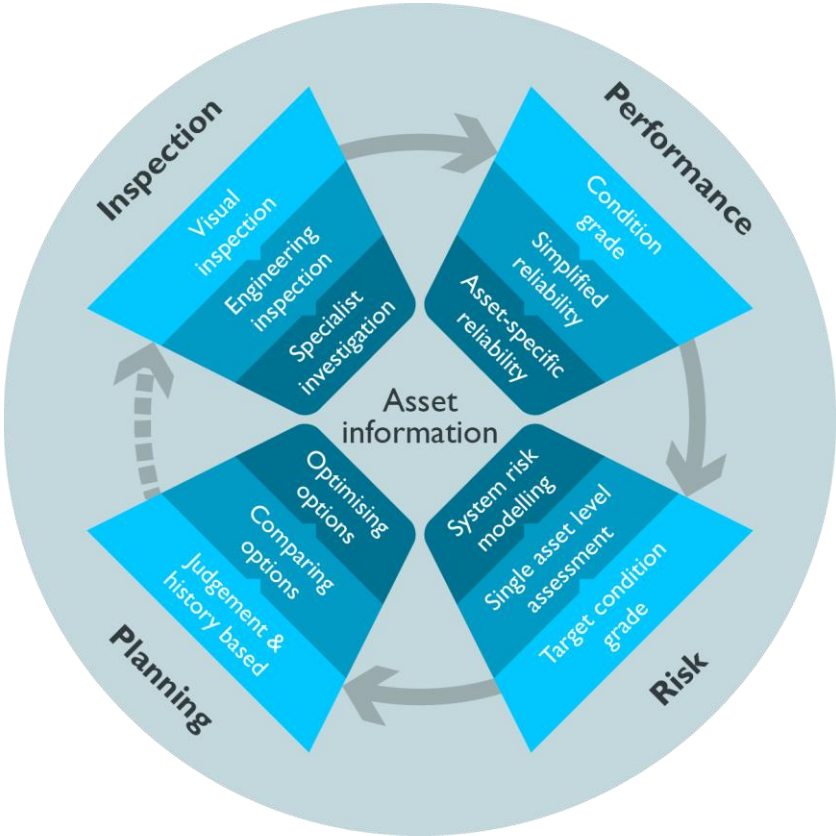

Figure 1.1 AP Tools framework

1.2 Improving fragility and deterioration curves

This report covers the product related to the performance assessment arm in the framework. It provides the methodology for using local knowledge to develop asset-specific fragility and deterioration curves. The method formed the basis for the development of the Custom Fragility Curve tool used to derive asset-specific fragility curves (see appendix). It also informed the improvement of part of the Whole Life Cost tool in which an asset deterioration curve can be adjusted. The curves developed are then used in the investment decision-making elements of the planning arm of the propeller.

The method builds on existing generic fragility and deterioration curves. These were primarily developed for national level assessment, but are also suitable for local scale assessment of less critical assets. More background on the existing curves is provided in Section 2.1. The new method translates practitioners' knowledge and understanding of the assets and their performance into asset-specific fragility and deterioration curves. As part of this project, the method was validated with a group of asset managers in the context of the case studies developed for the AP Tools project.

This research has a number of benefits. The main direct benefit is the production of curves that better represent the assets. This will improve the assessment of asset performance and flood risk at various levels:

- through the Risk Attribution Field Tool (RAFT) at a local level
- through the Modelling and Decision Support Framework 2 (MDSF2) at a system and catchment level

- through the National Flood Risk Assessment (NaFRA) and the Long-Term Investment Scenarios (LTIS) at national level

Another important benefit is that the local asset manager can input their local knowledge in the development of the curves (appropriately validated), and this will increase the ownership of and confidence in the curves, related tools and resulting datasets.

1.3 Key issues and concepts

It is expected that local calibration of the curves will not be appropriate for every asset and so this report aims to provide a middle tier approach. For many of the simple and less critical assets, the existing generic curves will probably remain adequate – this is the outer tier of the propeller arm shown in Figure 1.1. There is also an inner tier: for the most critical and complex assets, it may be worth developing curves based on specialist modelling and Monte Carlo analysis. This concept of a tiered approach is an important part of this report – the time and effort to apply the method has to be appropriate to the benefits derived from improved understanding.

It is seen as essential that the local asset managers can supply their knowledge in terms that are familiar to them. It is not realistic to expect most local staff to think in scientific and probabilistic terms; this translation has to happen within the tool. However, there is value in presenting the results to the users as this can help to generate buy-in and confidence. On the other hand, there is an identified risk of asset managers 'playing the system' in order to maximise funding. This also relates to the potential need for an audit trail and the allocation of confidence levels. Such issues were therefore addressed in the development and embedment of both the method and the associated tool.

For each type of local knowledge and information, there has to be an appropriate method of translating it into improved curves. Generally speaking, any local information is very likely to be an improvement compared with the broad assumptions behind the generic curves. However, care is necessary when combining the different pieces of information provided by the asset managers. In addition, the Custom Fragility Curve tool (see the appendix) has a limited scope; for example, it will not be possible to carry out significant Monte Carlo analysis at this stage of tool development. Although the methodology presented in this report does not take the limitations of the scope of the Custom Fragility Curve tool into consideration, the issue is addressed in the conclusions and recommendations (see Section 4).

1.4 General approach

Building on the concepts identified in the preceding PAMS and System Asset Management Plan (SAMP) optioneering studies (Royal HaskoningDHV 2013), the research team started by identifying the local information and knowledge that might be available and could support the validation of the curves. This was grouped into 6 information types. For each information type, the team developed a set of questions in a language suitable for local asset managers. The team also developed initial ideas for translation of the information to the curves.

The list of information types and associated questions was then discussed in detail with the wider AP Tools project team and with typical asset management staff as part of the case studies being used within the project. This helped to:

- assess the suitability of the method for use by local asset managers

- determine to what extent the identified information was available in practice
- inform the team's thinking about the percentage of assets for which the method would be appropriate

Three case studies were initiated with the aim of involving practitioners throughout the development of the AP Tools and methods for raised defences:

- Somerset – involving James Yarrow of the Environment Agency
- Exmouth and wider experience of the use of data and working practices in the Devon and Cornwall area – involving Tim Lee of the Environment Agency
- Thames Estuary focusing on the Isle of Dogs and Isle of Grain – involving Ed Morris of CH2M in his role with the Thames Estuary Asset Management 2100 (TEAM2100) project team

1.5 Structure of the report

Sections 2 and 3 discuss the methods for fragility curves and for deterioration curves respectively. This includes the validation of the method through the case studies.

Section 4 presents conclusions and recommendations for both types of curves.

2 Fragility curves

2.1 Background

Fragility curves represent the likelihood of breach of flood defences as a function of loading level. In a simplistic deterministic context, the likelihood of breach is assumed to be 0 when loading is below the design value, and 1 when the loading is above the design value. In a more realistic approach, there is a more gradual increase from 0 to 1 as loading increases and different failure modes become relevant. In addition, a gradual increase reflects the uncertainty around parameter values and performance models.

In England, flood defence fragility curves are an important part of the system flood risk models that are used at various levels:

- in NaFRA and LTIS – both national level
- in MDSF2, which aims to support system and catchment level decisions
- in RAFT, which the Environment Agency uses to assess criticality of assets that do not meet their target condition grade

Since the first versions of RAFT and the fragility curves were developed in the early 2000s, the intention has always been to apply a tiered approach, using simple curves where possible and more detailed ones for more critical and complex assets. Over time, a consensus developed that the higher tiers would require location-specific curves rather than more detailed generic ones. The development history of generic and asset-specific fragility curves is summarised below in Section 2.1.1 and Section 2.1.2 respectively.

2.1.1 Generic fragility curves

The first sets of curves were developed in the early 2000s, up to 2004. They were applied successfully in the various tools for national scale assessment and also implemented in MDSF2 and RAFT.

Over the years, various reviews took place that identified potential improvements, for example, in the PAMS project, the Thames Estuary 2100 (TE2100) strategy and as part of the review of flood defence asset performance during the summer 2007 floods. These reviews identified a number of potential improvements. In the meantime, the Environment Agency introduced its new AIMS, with an improved asset classification system.

A new set of generic fragility curves was developed for the Environment Agency in 2014, improving the original curves. These new curves use a more appropriate range of failure mechanisms and have been updated to account for the new defence classification system. Important improvements concerned:

- grass erosion resistance (changing the model parameters from conservative design values to realistic assessment values)
- the ability to better account for the height of vertical walls and the slope angle of embankments

2.1.2 Asset-specific curves

RELIABLE

RELIABLE is a flexible, software ‘reliability tool’, created within the FLOODsite project to assist in the generation of site-specific fragility curves by analysing the reliability of flood defences. The tool includes a total of 72 failure modes. It requires input about:

- flood defence geometry
- material properties
- potential failure mechanisms
- fault trees
- uncertainties

The tool then calculates structure-specific fragility curves based on Monte Carlo simulation.

The RELIABLE tool is intended only for high risk/cost assets due to the effort required in data collection and analysis. It is not currently set up for wider practitioner use.

TE2100

The TE2100 strategy was used as a testbed for various parts of the PAMS project which preceded the AP Tools programme. This included use of a system risk model with asset-specific fragility curves. The project used an ‘exemplar sites’ approach: a limited number of typical assets were identified and these were assumed to represent all of the assets along Thames Estuary. Detailed specialist analysis was carried out for each exemplar asset, using the RELIABLE tool in combination with advanced geotechnical modelling and expert judgement.

The pilot demonstrated that site-specific curves can be very different to the generic curves, in particular for the complex, often composite assets in the Thames Estuary. It also demonstrated that the exemplar approach can work well in practice. The resulting curves are now embedded in the Thames Estuary assessment methodology for asset refurbishment, change or replacement.

PAMS Phase 2 and SAMPs optioneering study

Alongside the development of the asset-specific curves in TE2100, the PAMS project carried out initial scoping of the potential for translating existing asset knowledge into the probabilistic context of fragility curves. This PAMS work package developed the original concepts of shifting and reshaping the generic curves to reflect:

- local knowledge from asset managers (for example, experience during flood events)
- deterministic design information (for example, Factors of Safety from design calculations)

These concepts were explored further in the SAMPS optioneering study (SC120011) in 2013. Working closely with a wide range of Environment Agency asset management staff, the study confirmed that the limited credibility of the generic fragility curves at asset level was an important obstacle for the use of system risk analysis tools for asset management planning. These findings formed the basis for this part of the AP Tools Phase 3 study.

2.2 Types of information for fragility curves

As discussed in Section 1.4, the research team started by identifying information types that could be available from local asset managers and could be used to calibrate the curves. The following types were identified for fragility curves:

- event information
- design information
- asset (sub-) types
- dominant failure modes
- asset information that is different to the generic curve assumptions
- condition grade and dominant features for deterioration
- irregularities and transitions

For each of these, the following sections assess how they could inform:

- the fragility curves
- the specific input required from the asset managers
- validation on the basis of the case studies
- an analysis of how the information could be translated technically into the curves

2.3 Event information

2.3.1 How it can inform fragility curves

If an asset has undergone a high loading event in recent years, there is real experience about its performance under loading. If the appropriate information about loading and asset response is available, and the asset has not changed significantly since, this information could be used to inform the fragility curve.

A number of cases can be distinguished.

- If the asset has survived the loading without sign of damage, this means the probability of breach at that loading level and condition grade is very low.
- If the asset showed signs of damage but has not been repaired since, this means the probability of breach at that loading level and condition grade is significant.
- If the asset breached and has been repaired without significant improvement, this means the probability of breach at that loading level and condition grade is very high (if the asset has been improved, then the design information can inform the curve; see Section 2.4).

2.3.2 Input required

The following inputs are required for this information type:

- Loading level during the event: water level for fluvial defences, wave overtopping for coastal defences
- Response of the defence to the loading: did it breach, show signs of damage or got through the event without any damage?
- Has the defence changed significantly since the event: yes or no?

2.3.3 Case study validation of availability of information

The case study asset managers reviewed the availability of this information type, with the following conclusions.

- Event information is available for more recent events, but information is lacking for more historic events. The information is also only likely to be available for more major/significant events.
- The information is not necessarily held by the team or individual responsible for assessing the asset performance and interested in producing the fragility curve. Although the data are available, the accessibility of such data may restrict its input into producing specific fragility curves.
- How the asset performs only tends to be recorded if the asset suffered damage, or if the asset is critical and therefore subject to post event inspections.
- Alterations/improvements to assets should be recorded but this information is not always available. The degree of information available is likely to depend on the level of alterations and improvements carried out.
- The format of event information varies across the case studies in terms of telemetry data and survey data.

2.3.4 Method for changing the curves

In general, event information can fix one point on the fragility curve, that is, the likelihood of breach at the loading level during the event for the defence's condition grade at that time.

Information about the defence's response will be qualitative, so there is a need to define classes of response with an associated assumed probability of breach. Initial suggested values are:

- 1% if the asset has survived
- 50% if there was some damage (maybe with sub-classes)
- 95% if the asset breached

Once the single point on the curve of the current condition grade has been fixed, the rest of that curve needs to be adapted. The simplest approach would be to shift all curves horizontally over the same distance (that is, applying the same absolute change in loading level as for the event point). However, doing this in a tapered way instead is suggested, that is, gradually reducing the change from the generic curve with increasing difference from the experienced loading level.

Finally, the curves for the other condition grades need to be adapted. This could be done proportionally to the changes made to the curve for the current condition grade, possibly tapered for the condition grades further away from the current condition grade.

2.4 Design information

2.4.1 How it can inform fragility curves

If design calculations are available, their results could be used to define the probability of breach at design loading levels.

This would typically be valid for condition grade 1, as this is defined as the condition of a newly constructed defence. However, there might be cases where calculations are available to assess existing defences with a poorer condition grade.

If detailed calculations are available, the resulting Factor of Safety could be used to inform the curves. Even if this is not the case, however, the fact that the asset was designed according to good practice standards and codes can be sufficient to infer a typical probability of breach at a typical loading level in relation to a standard 'freeboard' allowance.

Information about parameter values from design (and other sources) is discussed separately in Section 2.7.

2.4.2 Input required

For this information type, evidence is required that the asset was designed according to good practice standards and codes.

The reliability of the curves can be further improved with design calculation results:

- analysis of dominant failure modes
- calculated Factor of Safety – possibly with sensitivity testing of the Factor of Safety for design variables

In some cases, the design calculations may even include fragility curve type information (for example, based on probabilistic modules of geotechnical models).

2.4.3 Case study validation of availability of information

The case study asset managers reviewed the availability of this information type, with the following conclusions.

- This information is likely to be available in the health and safety files for post 1996 designs, although not all files will include calculations. Building Information Modelling will also aid the collation of such information for forthcoming design changes.
- Even where recent design information is available, this is unlikely to include fragility curve information from advanced geotechnical models as it is not a specified output.

- It is unlikely that the design information will be available for older assets, or that these assets would meet the current standards.
- Some designs will not meet the design standards due to site constraints. However, knowledge of which assets this applies to will ensure a more specific fragility curve is used.
- It is common for the rear height of the defence to be different to the front height. Where specific design information is not available, there should be knowledge of any difference in the rear height of the defence compared with the front. However, this may not be held or known by the team or individual responsible for assessing the asset performance and interested in producing the fragility curve. Exact differences are also likely to require a detailed survey.

2.4.4 Method for changing the curves

A design according to good practice standards is likely to have a probability of breach at design loading between 1 and 10%; for now a value of 5% is suggested.

Translation of the Factor of Safety to a probability of breach is not straightforward and the project team are not aware of an established relationship. For this project, a pragmatic approach was considered likely to be adequate, for example, based on the relative change of the Factor of Safety compared with the required Factor of Safety based on good practice standards.

Any available fragility curve information could be directly translated to an asset-specific curve if the information covers all relevant failure modes. However, it is not thought worthwhile to develop the method and tool for the few special cases where this information is available; it is suggested that this should be dealt with on a case-by-case basis.

2.5 Asset (sub-)types

2.5.1 How it can inform fragility curves

The generic curves assume that each asset belongs to one asset type and that they are based on assumed asset sub-types. The following asset types were assumed in the development of the generic curves:

- Vertical walls (coastal and fluvial): based on soil retaining walls (but also applied to flood walls)
- Sheet pile walls (coastal and fluvial): based on cantilevered walls (but also applied to anchored walls)
- Embankments (coastal and fluvial): earth embankments with and without grass protection and/or other protection on landward face and/or crest and/or waterward face.
- Shingle beach: no specific sub-type assumed

For assets that are actually hybrids between these asset types, it may be possible to improve the fragility curves by interpolating between existing generic curves.

If an asset is of a different sub-type, the necessarily simple approach developed in this study is unlikely to be appropriate. If such assets are critical, advanced analysis to develop a bespoke curve may be appropriate.

2.5.2 Input required

For hybrid asset types, information on the degree to which an asset belongs to each type is required. It is important to relate this degree to the flood defence function. At the basic level of this method, an intuitive approach supported by guidance and examples is likely to be adequate.

2.5.3 Case study validation of availability of information

The case study asset managers did not explicitly review this information type, but did comment that the most common type of hybrid asset concern sheet piled embankments. There are other examples, but these are not as common as the typical generic masonry wall or embankments

When presented with HR Wallingford's initial ideas for the Custom Fragility Curve tool which proposed using slider bars to define the proportions of types for hybrid assets, the response was generally positive.

2.5.4 Method for changing the curves

The degree to which an asset belongs to each asset type for which a generic curve is available can enable a weighted interpolation between the existing curves.

For critical assets of a different sub-type, this type of information could act as a trigger for some form of more advanced analysis to determine asset-specific curves.

2.6 Dominant failure modes

2.6.1 How it can inform fragility curves

The generic curves are based on assumed asset dominant failure modes. Local knowledge that a different failure mode is dominant (for the whole or part of the loading range) could help to inform asset-specific curves.

The following failure modes were assumed in the development of the generic curves:

- Vertical walls fluvial: failure mode horizontal sliding
- Vertical walls coastal: HR Wallingford (2014) presents a new set of curves based on failure mode toe scour but suggests retention, for the time being, of the previously developed curves based on landward slope erosion
- Sheet pile walls (coastal and fluvial): bending failure
- Embankments fluvial: piping for water level below the crest, overtopping causing erosion for water level above the crest
- Embankments coastal: seaward face erosion and landward face erosion
- Shingle beach: horizontal crest retreat

2.6.2 Input required

This requires an assessment of:

- whether the assumed dominant failure mode is relevant for the asset
- which modes are dominant and relevant

This information could be based on local experience with asset failure, and possibly also on expert judgement and local knowledge.

2.6.3 Case study validation of availability of information

The case study asset managers reviewed the availability of this information type, with the following conclusions.

- Asset managers have a good understanding of failures actually experienced in their area and will be able to translate this understanding to their wider asset base.
- Local failure modes experienced include:
  - animal and vermin damage within embankments
  - scour damage from overtopping, particularly where embankments have steep back slopes
  - failure during tidal drawdown where assets are tidally influenced

2.6.4 Method for changing the curves

This information type could be addressed by making additional generic sets of fragility curves available for other failure modes. This would require significant work (beyond the scope of Phase 3 of the AP Tools project), but it would enable the tool to pick the appropriate generic fragility curve or even combine or interpolate between multiple curves.

A simpler approach without a need for additional generic curves is also conceivable. If a different failure mode is dominant, this suggests that the generic fragility curve is very likely to be too optimistic for that asset and so changing the curve to reflect higher fragility would be justified. The extent of this change would need to be determined, and this is difficult at a generic level. In conclusion, an approach with additional generic curves is strongly preferable.

For critical assets, this information type could act as a trigger for some form of more advanced analysis to determine asset-specific curves.

2.7 Asset information that is different to the generic curve assumptions

2.7.1 How it can inform fragility curves

The generic curves are based on assumed fixed values for a range of geotechnical, geometric and materials parameters. This typically concerns information not directly available from AIMS for all assets, which is why values had to be assumed to enable national scale use of the curves. Knowledge of actual parameter values for the assets, and how these differ from the assumed values, could help improve the curves to match specific assets.

The type of parameters for which the generic curves are based on assumed values are listed here. This is based on HR Wallingford (2014), which also contains the actual values assumed for each parameter. Only those parameters used for the most recent State of the Nation analysis are listed here.

- Vertical walls fluvial:
  - wall material and width
  - geotechnical parameters of surrounding soil (separate for sand and clay)
  - surcharge
  - levels of soil and water relative to the crest (retaining height of the wall has been incorporated within the curve and so did not require assumptions)
- Vertical walls coastal: overtopping rate under incident wave conditions based on beach level at the toe
- Sheet pile walls (fluvial and coastal):
  - wall material strength
  - geotechnical parameters of surrounding soil (separate for sand and clay)
  - surcharge
  - levels of soil and water relative to the crest
  - relationship between sheet pile toe depth and wall height (retaining height of the wall has been incorporated within the curve and so did not require assumptions – with a caveat that the curves appear less representative for lower walls)
- Embankments fluvial:
  - Water level below crest (piping) – seepage length (separate curves for narrow and wide with assumed lengths), geotechnical parameters of the subsoil, thickness of permeable layer
  - Water level above crest (landward slope erosion) – grass quality, landward slope angle, hydraulic roughness, storm duration, embankment height
- Embankments coastal (landward slope erosion):
  - degree of protection of crest and landward slope
  - grass parameters (root depth, clay thickness, erosion resistance)
  - landward slope angle
  - hydraulic roughness
  - storm duration
  - embankment height
- Shingle beach: beach material and ridge width (beach slope is seen as relevant, but could not be reflected explicitly)

The curves are not equally sensitive to all these parameters. In addition, local asset managers are unlikely to have information (unless from design) for some of these parameters. The method could focus on the parameters with the greatest impact.

2.7.2 Input required

Asset-level values are required for the relevant parameters. It may be adequate to ask the user for classes of values rather than exact values.

2.7.3 Case study validation of availability of information

The case study asset managers reviewed the availability of this information type, with the following conclusions.

- Crest widths on some embankments considered within the case studies are considerably less than the 7.5m wide 'narrow crest' used for the generic curves.
- Historic embankments tend to have steeper slopes, whereas newer or altered assets tend to have slopes between a 1 in 3 and 1 in 5.
- The slope data are not always readily available.

2.7.4 Method for changing the curves

Accurate representation of different parameter values would require some form of probabilistic analysis, which may not be realistic within the scope of a middle tier method and tool.

For the most important parameters, however, it may be possible to:

- determine a range for which the existing curves are appropriate
- develop a library of generic relationships (in effect new generic curves) for adapting the curves for values outside those ranges

As the models for the existing curves were only recently developed, this is likely to require limited effort.

A simpler approach without a need for additional generic curves is also conceivable, that is, to use limited analysis and expert judgement in the development of the tool to derive the relationship between parameter value and fragility curve. This approach is not preferable, as the limited extra effort needed to develop new generic curves is likely to be worthwhile.

2.8 Condition grade and dominant features for deterioration

2.8.1 How it can inform fragility curves

The condition grade is based on visual inspection according to the Condition Assessment Manual (Environment Agency 2006) and is recorded in AIMS.

There is a separate fragility curve for each of the 5 condition grades. This plays an important role in the assessment of existing flood risk, but they also determine how calculated risk changes over time via the deterioration curves (see Section 3).

The generic curves per condition grade are based on assumed changes in the value of chosen indicator parameters. Local knowledge and information about the parameters that determine the condition grade for a specific asset could inform a more appropriate relationship between the curves for different condition grades, and improve how the curves reflect the influence of deterioration on asset performance and flood risk. This could also relate to different failure modes being dominant (see Section 2.6).

The chosen parameters to reflect different condition grades are listed below. They are based on HR Wallingford (2014), which also contains the actual values assumed at each condition grade:

- Vertical walls coastal: depth of toe scour
- Vertical walls fluvial: density of wall material
- Sheet pile walls (fluvial and coastal): reduction of yield strength due to loss of steel thickness by corrosion
- Embankments fluvial:
  - water level below crest (piping): reduction of seepage length
  - water level above crest: reduction of grass quality class
- Embankments coastal (landward slope erosion): reduction of erosion resistance
- Shingle: reduction of beach width

In addition, local knowledge could help to determine the condition grade more accurately. In reality, the condition of assets is somewhere in between the 5 defined grades, often between condition grade 2 and condition grade 4. This is strictly outside the scope of this study (it concerns a different approach to determining condition grade), but could be combined with a tool for fragility curve calibration.

2.8.2 Input required

This will require information on the dominant deterioration process for particular assets. This could be based on actual observed deterioration over time as recorded in formal inspection. It could also be based on more general understanding of the assets and their environment.

There is no need to provide quantitative information: the condition grades as defined and illustrated in the Condition Assessment Manual are treated as a given for this purpose. The information could, for example, be provided via a dropdown menu.

2.8.3 Case study validation of availability of information

The case study asset managers reviewed the availability of this information type, with the following conclusions.

- For embankments, the damage and condition of the crest was considered the main factor determining their condition grade, while for masonry assets it was the exposure of foundations.

- Aspects that would dominate future deterioration to the assets within the case studies were considered to be masonry cracks and wall movement. For embankments, it would be further overtopping which would lead to scour damage, as well as animal damage.

2.8.4 Method for changing the curves

This will require additional generic curves, pre-calculated based on different indicator parameters and associated values reflecting all the condition grades. In some cases this will relate to other dominant failure modes (see Section 2.6).

2.9 Irregularities and transitions

2.9.1 How it can inform fragility curves

Defences are known to typically fail at transition points or where irregularities exist such as:

- old channels crossing the assets
- changes in subsoil or asset structure
- presence of foreign objects
- animal infestation

These are locations where strength is lower than neighbouring sections (or in some cases, loading is higher). Local knowledge could be used to identify these weaknesses, possibly quantify this to an extent and use that information to correct the curves.

2.9.2 Input required

Required information includes the type and extent of the irregularity. The method and tool will need to be based on qualitative information, possibly using classes to describe extent and seriousness of the issue. It will also be important to confirm whether any measures have been taken to mitigate the impact.

2.9.3 Case study validation of availability of information

The case study asset managers reviewed the availability of this information type, with the following conclusion.

- Local irregularities included those within historic embankments. In some areas, these are constructed of silt and therefore more vulnerable to scour issues.

2.9.4 Method for changing the curves

At the basic level of this method and tool, implementation could consist of a simple increase of the likelihood of breach by a notional value to be determined with judgement-based analysis in the development of the tool. It could be considered to limit the reduction for the higher condition grades, as these already account for some of the irregularities.

Irregularities could be captured in additional generic fragility curves by choosing different parameter values.

For critical assets with irregularities, this type of information could act as a trigger for some form of more advanced analysis to determine asset-specific curves, although it may be more appropriate to use the analysis to develop mitigation measures.

3 Deterioration curves

3.1 Background

Deterioration curves represent the expected change over time of a flood risk management asset's performance. The Environment Agency uses a set of curves tailored to its specific context developed in project SC060078 (Environment Agency 2013). These curves reflect the change over time of the condition grade as defined in the Condition Assessment Manual (Environment Agency 2006), used as a proxy for asset performance. In reality, performance also depends on factors not captured in the condition grade such as geotechnical and geometrical factors. In theory, it would be possible to relate deterioration directly to fragility but this would require fundamental changes and is beyond the scope of this study.

The deterioration curves are available for a wide range of assets:

- vertical walls
- sheet piled structures
- demountable defences
- embankments
- sloping walls with slope protection/revetment
- culverts
- dunes and shingle beaches
- control structures
- channels
- weirs
- outfalls
- flap valves
- moveable gates (manual and electrical)
- debris screens
- flood gates and barriers

For each asset type, there are curves to reflect the maintenance regime (basic/medium/high) and other factors such as environmental exposure and quality of materials (slow/medium/fast).

The generic curves are based on expert judgement and knowledge on typical deterioration rates. There has been some research to explore a more science-based approach for FCRM assets (for example, PhD research by F. Buijs) but this has not yet been applied in practice.

The existing 'generic' deterioration curves are available as tables and graphics, and also in the whole life cost tool developed as part of project SC060078. This tool uses the deterioration curves as input for a whole life cost analysis, based on asset life and unit costs for standardised maintenance regimes. Improvements have been made to this whole life cost tool as part of Phase 3 of the AP Tools project to make it more suitable for practical use.

The generic deterioration curves form part of the guidance available to the Environment Agency's asset management teams for the preparation of SAMPs. Staff can use the curves to develop maintenance regimes and the associated investment profiles that are entered into the SAMPs application. In practice, use of the curves for this purpose is limited.

The generic curves form part of the Flood and Coastal Erosion Tool (FaCET), the long-term investment planning toolkit which supports LTIS. The curves determine the development of asset condition grade over time in the model, which determines asset performance and can trigger intervention and investment. They can also be used in MDSF2 for the same purpose at a more local level. The curves are also used in strategies and studies to provide indications of residual life.

In the TE2100 project, asset-specific deterioration curves were developed for the representative exemplar assets, alongside fragility curves. These were then applied to the whole of the TE2100 project area and used in its modelling of future asset management and investment.

3.2 Types of information for deterioration curves

As discussed in Section 1.4, the research team started by identifying information types that could be available from local asset managers and could be used to calibrate the curves. The following 4 types were identified for deterioration curves:

- history of condition grade development
- local asset-specific information on type, maintenance regime and other factors such as environmental exposure, quality of materials
- locally dominant deterioration mechanisms
- overall estimate of residual life based on local knowledge and judgement

For each of these, the sections below assess how they could:

- inform the deterioration curves
- the specific input required from the asset managers
- validation on the basis of the case studies
- an analysis of how the information could be translated technically into the curves

3.3 History of condition grade development

3.3.1 How it can inform deterioration curves

Local knowledge of the history of an asset's deterioration under a known maintenance regime and loading history can inform durations between condition grades. Insight into the condition grade's historic development can inform how it is expected to develop in the future.

Basing the method on the overall condition grade is suggested; this is based on a combination of element level condition grades. However, it may be worthwhile to use this overall condition grade with a higher level of precision (for example, using years to condition grade transition, or one decimal point) for the particular purpose of forecasting (recognising the risk of suggesting a higher precision than justified). Such a decimal condition grade is also expected to become available from the Whole Life Cost tool (see SC140005/R1). It may also be possible to carry out the actual analysis at element level (extrapolate for each element and then combine into an overall condition grade); this may be justified for more critical assets, but is seen as too detailed for this tier.

The actual deterioration rate will have been influenced by the actual asset type, maintenance regime, exposure and quality of materials. In theory, information about this could be used to inform the interpretation of the historic trend. However, this is seen as too advanced for this tier; these factors can be used in a different way to fine-tune deterioration curves (see Section 3.4).

3.3.2 Input required

The main input concerns the development over time of the asset's overall condition grade. If available, this could be the calculated combination of element condition grades, potentially at one decimal point (for example, a condition grade of 3.5).

3.3.3 Case study validation of availability of information

The case study asset managers reviewed the availability of this information type, with the following conclusions.

- Condition grades have been recorded for approximately 10 years. However the historic grades are only accessible if the National Flood and Coastal Defence Database remains available.
- Major maintenance works may be included in SAMPs, though regular maintenance tends not to be recorded.

3.3.4 Method for changing the curves

Various methods are possible, with a different weighting for either the observed historic trend or the existing generic curves. The proposed method is to use the historic condition grade trend to calibrate that generic curve for the most appropriate asset type, historic maintenance regime and other factors such as environmental exposure and quality of materials.

The tool would calculate:

- the average deterioration rate (condition grade per year) over the timespan of the historic records
- a factor based on the difference with the deterioration rate according to the generic curve

Moderating how much the rate can deviate from the generic curve in this tier is suggested, for example, by limiting the factor to twice as slow or fast as the appropriate generic curve. The same factor would be applied to the whole deterioration curve (that is, also for other condition grades). When developing a deterioration curve for the scenario of a changing maintenance regime, the same calculated (and moderated) factor could be applied to the generic curve for that regime. It is proposed to apply this approach only if at least 5 historic records are available.

Potential alternative approaches that rely either less or more on the existing generic curves are:

- Less: direct extrapolation of the historic trend
- More: only use the historic trend to select the most appropriate generic curve (in terms of asset type, maintenance regime, exposure and quality of materials)

For critical assets, an inner tier approach for developing asset-specific curves could be justified. This would typically include use of the condition grade history.

3.4 Local specific asset type, maintenance regime, exposure and quality of materials

3.4.1 How it can inform deterioration curves

The generic deterioration curves are based on:

- generalised asset types
- 3 maintenance regimes
- 3 exposure/quality of materials classes

In reality, these factors are some hybrid between the defined classes; a more accurate description can help fine-tune asset-specific deterioration curves.

The asset types, maintenance regimes and exposure/material quality classes are described in Environment Agency (2013):

- Asset type: 16 types with various sub-types
- Maintenance regime: basic/medium/high reflecting frequency and intensity of inspection, maintenance, repair and refurbishment in line with the Environment Agency's Asset Management Maintenance Standards (Environment Agency 2010)
- Exposure/quality of materials: slow/medium/fast. These factors have not been defined in detail; they are only used qualitatively, representing a broad range of factors that influence deterioration. 'Slowest' is characterised by a sheltered location and/or high quality materials and construction, while 'fast' would relate to an exposed location and/or poor quality materials. 'Medium' is considered a typical rate, providing a mid-range value.

3.4.2 Input required

Knowledge of the asset's type, maintenance regime and exposure/quality of materials can be compared with the generalised classes. At this tier, it is proposed that asset managers should use their judgement to determine how the actual regime compares to the 3 generic regimes, for example by using a slider bar as in the Custom Fragility Curve tool.

3.4.3 Case study validation of availability of information

The case study asset managers reviewed the availability of this information type, with the following conclusions.

- Maintenance regimes over the years have been inconsistent due to funding, access and landowner use (for grazing), making it difficult to select one single historic regime.
- Assets where the Environment Agency is not the riparian owner have a less consistent maintenance regime. The maintenance may not be carried out to the level the Environment Agency would carry it out.

3.4.4 Method for changing the curves

The quality of the actual maintenance regime compared with the generic regimes can be used directly to interpolate between the generic curves.

At this tier, it is proposed to remain within the defined lowest and highest generic regimes. For critical assets, a higher tier assessment including more extreme regimes may be justified.

3.5 Dominant factors for deterioration locally

3.5.1 How it can inform deterioration curves

The generic curves are based on expert considerations implicitly covering all potential deterioration mechanisms. These are listed in Section 3 of the technical report for project SC060078 (Environment Agency 2013). Local knowledge of dominant mechanisms and of how they are likely to affect the condition grade could help to develop local curves.

Due to the non-quantified relationship between deterioration processes and generic curves, it is difficult to use this type of local information to calibrate the generic curves. It may be possible to create a bespoke deterioration curve in cases with a clearly identified, specific ongoing deterioration process that is known to determine future condition grades.

At this tier, it is not realistic to provide a method/tool that translates local information about specific deterioration modes into deterioration curves. This would require higher tier location-specific assessment, which may be justified for critical assets.

However, it is possible at this tier to enable a user to enter expected deterioration rates/residual life estimates, available based on local scale assessment. These can be translated directly into a deterioration curve. This is described in Section 3.6.

On that basis, there is no need for this information type for sub-sections describing the input required, case study validation and method for changing the curves.

3.6 Estimate of residual life based on local knowledge and judgement

3.6.1 How it can inform deterioration curves

There will be cases where an asset manager has good quality information about expected deterioration rates (for example, based on more detailed local study or assessment). This information could be about part of the information required for a deterioration curve (for example, years until next condition grade transition), but also the full deterioration curve.

An important issue for this information type is to assess:

- the level of confidence in the local assessment
- whether this is more reliable than the generic curves (which are not location-specific, but consistent and based on recognised expert judgement)

It is proposed that, in principle, this form of local information should be seen as more reliable than the generic curves, certainly for local use. However, there may be a need to require a certain level of evidence before accepting the resulting curves for wider use (for example, in FaCET or MDSF2).

3.6.2 Input required

The following information could be available and serve as input:

- time until next condition grade transition (years)
- time until each future condition grade transition (years for each condition grade poorer than current condition grade)
- full deterioration curve including (years from new built to condition grade 2, 3, 4 and 5, plus information on current position of asset on the curve)

3.6.3 Case study validation of availability of information

The case study asset managers reviewed the availability of this information type, with the following conclusion:

- There is the knowledge available locally to estimate the number of years until the assets reach the next condition grade and condition grade 5.

3.6.4 Method for changing the curves

If a full profile of deterioration over time is available, this can be translated directly to a deterioration curve.

If the information consists of the time until all future condition grade transitions:

- the initial part of the curve up to the existing condition grade can be based on the appropriate generic curve
- the later part can be based directly on the information supplied

If the information consists only of the expected time until the next condition grade:

- the initial part of the curve up to the existing condition grade can be based on the appropriate generic curve
- the time until the next transition can be based directly on the information supplied
- the later part until condition grade 5 can be based on the appropriate generic curve – it may be possible to factor this duration, based on the supplied time until the next transition compared with the generic curve

4 Conclusions and recommendations

4.1 General observations

In addition to the analysis in Sections **Error! Reference source not found.** and 3 specific to fragility and deterioration curves respectively, this section contains some more generic observations raised by both the project team and the case studies.

4.1.1 Confidence in user information

The level of confidence in the local information could influence how it is used to calibrate the curves.

The degree of confidence could be used to determine the degree of change to the generic curves, possibly by making smaller changes from the generic ones if user confidence is low. It could also be used to assign confidence levels to the resulting fragility curves (if relevant for translation to confidence in flooding probability and risk) and as part of an audit trail.

It is important to realise that normally any local information is likely to be more accurate at asset level than the national level broad assumptions used in the development of the generic curves.

4.1.2 Suitability for typical users

As indicated in Section 1.3, there is a balance to be found between the proportion of assets (related to their criticality) for which the method is suitable, the level of effort that is realistic and staff competencies required to apply the method. User feedback as part of the case study workshop suggested the following.

- Local improvement of fragility curves is seen as very important and so it would be worthwhile to find the required staff resource and time.
- This could largely be a one-off process and would only have to be repeated if new information becomes available or the asset changes.
- This process could start with the more critical assets, but in some cases it may be more efficient to combine it with ongoing asset management activities (for example, refurbishment or improvement works).
- Broadly speaking, the type of questions suggested for the tool is appropriate for the competency level of Environment Agency Area asset management teams. It will depend on specific local circumstances as to which function in the team would be best placed for this task.

4.2 Conclusions for fragility curves

4.2.1 Case study findings

The case study validation has shown that:

- the method meets a need for Area asset management teams
- the teams would be willing to make resources available
- the method can be designed to suit competency levels, possibly with limited training

The required information types are available (where relevant) or can be made available for critical assets. Often, if the information is not available, the generic curves are likely to be adequate.

In general, there is likely to be less information available about ‘low consequence’ assets; however, these typically receive less maintenance which makes them more likely to breach.

4.2.2 Suitability of information types

The analysis in Section **Error! Reference source not found.** shows that, of the information types that could help inform asset-level fragility curves, some are more suitable than others for the pragmatic and user-focused approach envisaged. The most important factor is how the information can be translated into fragility curves (Table 4.1). The following routes have been identified:

1. Information type can be used directly to shift or reshape existing curves, possibly by interpolation between existing curves. This means that:
    - limited work would be required to agree the details of the ‘translation’
    - the information type could potentially be implemented in the Custom Fragility Curve tool (see appendix)
2. Information type would require the development of new generic curves. This means it is suitable for the pragmatic method and tool, but would require significant work before it could be implemented.
3. Information type would require the tool to run the Monte Carlo analysis itself, making it not suitable for the pragmatic tool. However, it could still be valuable for more advanced approaches to developing asset-level curves.

It is possible to further improve the return on investment for the development of asset-specific curves by focusing the effort on typical assets and then using these as exemplars that can be applied to a wider group of assets. This approach was used on the TE2100 study using advanced analysis to develop the curves for the exemplar sites.

A similar exemplar approach could also be used on the basis of advanced analysis (using RELIABLE or similar) instead of the user-focused tool. This could have the benefits of more accurate curves and less reliance on asset management staff resource, but it has the downside of less involvement and resulting ownership from asset management staff.

Table 4.1 Translation of information types to fragility curves

Information to inform local fragility	How to implement		
	Route 1	Route 2	Route 3
Event information	Shift/reshape for event loading		
Design information	Shift/reshape for design load or Factor of Safety		Advanced analysis if fragility curves are available
Asset (sub-) types	Interpolation for hybrid assets	New generic curves for asset types not covered by existing curves	Likely to be justified for critical assets
Dominant failure modes	Pragmatic increase of likelihood of breach if other mode is dominant (not preferred)	New generic curves for modes not covered by existing curves	Likely to be justified for critical assets
Asset information that is different to the generic curve assumptions	Pragmatic change to likelihood of breach if values are outside range of existing curves (not preferred)	New generic curves for parameter range not covered by existing curves	
Condition grade and dominant features for deterioration	Interpolation between generic curves for more accurate condition grade (strictly not in scope)	New generic curves for other dominant deterioration features	
Irregularities and transitions	Shift/reshape to reflect increased fragility	New generic curves for typical irregularities	

4.3 Recommendations for fragility curves

Different information types will require different approaches for translation into a pragmatic tool for asset-specific fragility curves (Table 4.1). A phased approach is recommended, starting with a simple tool that captures the information types that are easiest to incorporate. This will enable initial benefits to be generated, while also providing a proof of concept that can be built on in the next steps.

The recommended stages are as follows:

- Step 1: Interpolation between existing graphs for hybrid assets (and condition grades) (implemented in the Custom Fragility Curve tool)

- Step 2: Add functionality to enter event information, design information and irregularities, leading to shift and reshaping of curves (to be explored and possibly implemented in the Custom Fragility Curve tool)
- Step 3: Development of additional generic fragility curves for additional asset types, failure modes, parameter value ranges, deterioration modes and irregularities – expanding the tool to capture these information types and enable interpolation between curves

It is recommended that the Environment Agency considers how this process can be embedded into its organisation, including elements such as processes and capacity building.

It is also recommended that the Environment Agency plans for incorporation of the resulting fragility curves into relevant systems. As recommended in earlier phases of the AP Tools project, the obvious location to store asset-level fragility curves is in AIMS.

4.4 Conclusions for deterioration curves

4.4.1 Case study findings

Compared with fragility curves, deterioration curves are more intuitively understandable for asset managers, partly because they are not based on complex theoretical analysis. The information required is typically available.

However, there is limited evidence that the existing generic curves are being used in practice by asset managers in the production of SAMPs or otherwise. More local ownership of the curves might support this, but there may be a need to review either their format to ensure that they provide the information that asset managers need more directly, or the associated process.

4.4.2 Suitability of information types

The analysis in Section 3 shows that the information types considered are all potentially suitable for the pragmatic development of asset-specific deterioration curves, using different approaches:

- Historic condition grade trend: reshape existing curves
- Asset-specific information on type, maintenance, exposure/quality of materials: interpolate between existing curves (similar to the Custom Fragility Curve tool for fragility curves)
- Overall assessment of residual life: enable user to define new curves (or parts of curves)

4.5 Recommendations for deterioration curves

The 3 approaches identified in Section 4.4.2 are complementary and so, in principle, they could all be operationalised, potentially in the Custom Fragility Curve tool. An alternative may be to make this part of the Whole Life Cost tool further developed[1] as part of the AP Tools project.

It is recommended that the Environment Agency considers how this process can be embedded into its organisation, including elements such as processes and capacity building.

It is also recommended that the Environment Agency plans for incorporation of the resulting deterioration curves into relevant systems. As recommended in earlier phases of the AP Tools project, the obvious location to store asset-level curves is in AIMS.

[1] Note: Deterioration curves can be adjusted within the improved Whole Life Cost tool – refer to AP Tools Final report SC140005/R1

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List of abbreviations

AIMS	Asset Information Management System [Environment Agency]
AP Tools	Asset Performance Tools
CAMC	Creating Asset Management Capacity [Environment Agency]
FaCET	Flood and Coastal Erosion Toolkit
FCRM	Flood and Coastal Risk Management [Environment Agency]
LTIS	Long-Term Investment Scenarios
MDSF2	Modelling and Decision Support Framework 2
NaFRA	National Flood Risk Assessment
PAMS	Performance-based Asset Management System
RAFT	Risk Attribution Field Tool
RASP	Risk Assessment of Flood and Coastal Defence for Strategic Planning
SAMP	System Asset Management Plan
TE2100	Thames Estuary 2100 [Environment Agency project]
TEAM2100	Thames Estuary Asset Management 2100 [Environment Agency programme]

Appendix: Technical description of custom fragility curve tool

This appendix describes the implementation of the Custom Fragility Curve tool, which was developed based on this report.

A.1 General introduction

There are a suite of generic fragility curves that can be used to estimate the probability of failure of an asset for a given loading condition. While extremely useful, these generic curves rely on the underlying representation used to generate them being an accurate description of the asset under investigation.

The purpose of the Custom Fragility Curve Tool is to help users to estimate the probability of failure of a linear asset across a full range of loading conditions. By rating an asset's likeness to a collection of attributes, the tool allows the users to quickly generate a bespoke estimation of failure probability based on existing generic fragility curves.

The tool's objective is to translate practitioners' knowledge and understanding of the assets and their performance into asset-specific fragility and deterioration curves. The tool is based on a Microsoft® Excel spreadsheet designed to:

- provide an intuitive and easy-to-use graphical interface
- keep input data to the bare minimum
- use only local knowledge and close-to-hand information – likely to be asset type(s), basic geometry, visual condition grade for each component asset type(s)
- output a bespoke estimate of the probability of failure of an asset under a full range of loading conditions
- allow an assessment of an asset to be made in less than one hour

A.2 Interface

The interface is intuitive and easy-to-use. It uses only local knowledge and close-to-hand information. Figure A.1. shows some example screens.

The tool requests information needed for attribution and assessment, using slider bars to allow users to rate the similarity to relevant images or descriptions.

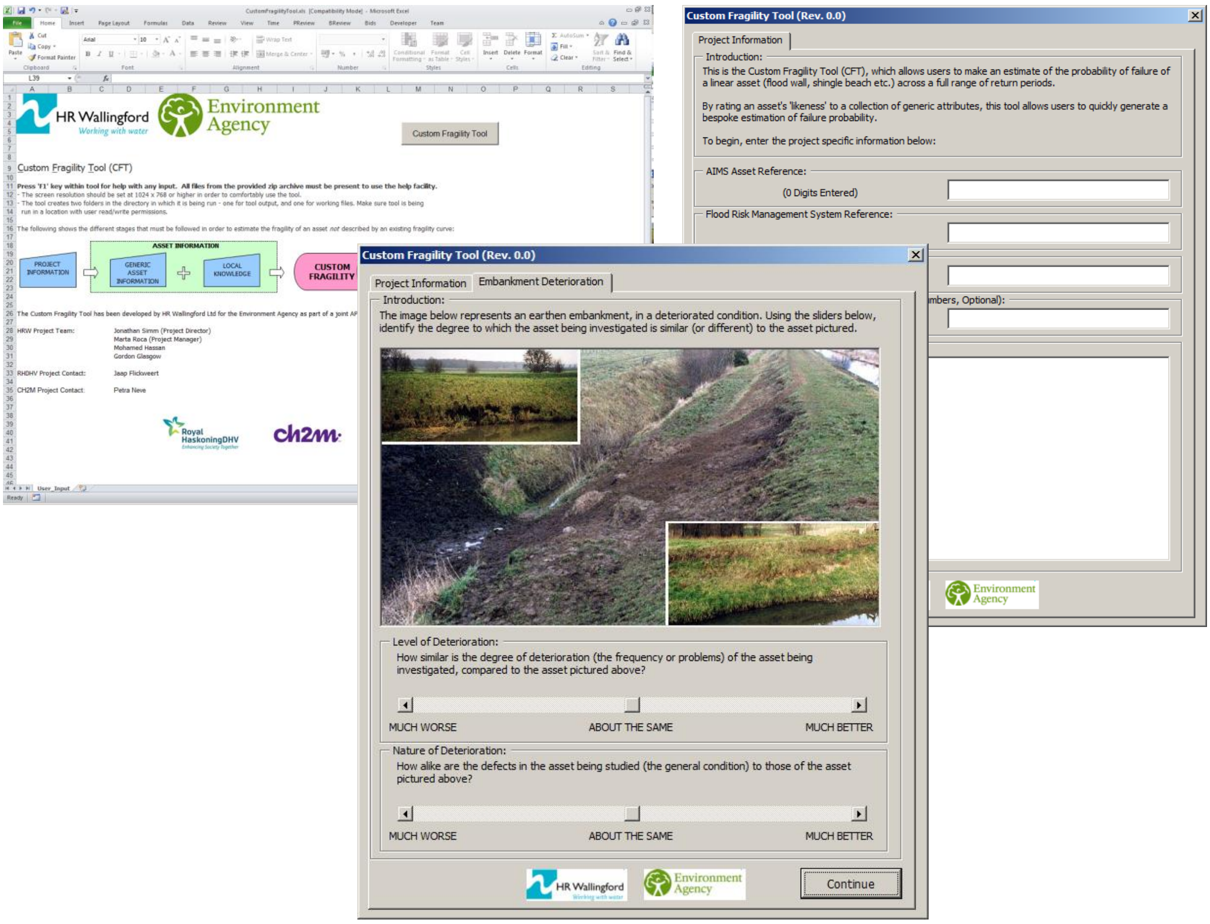

Figure A.1 Example screens from the Custom Fragility Curve tool

A.3 Description of the tool

The tool's starting assumption is that the majority of raised, linear defences are imperfectly described by a single generic asset type, but instead have a similarity to more than one generic fragility curve.

This assumption means that, instead of selecting a single fragility curve to represent an asset, a weighted sum of all fragility curves should be used. The weighting is called the 'Membership', and it is assumed to lie in the range of 0.0 (no likeness) to 1.0 (strong likeness). The key concept behind the approach is fuzzy logic, a technique designed to help answer/understand qualitative and uncertain questions. The concept is applied to both the Risk Assessment of Flood and Coastal Defence for Strategic Planning (RASP) type and the condition grade.

Using this additional information, the probability of failure of an asset on a given load (l) can be calculated by summing the product of probability of failure and membership, across all n generic types:

$$pFail(l) = \begin{bmatrix} Membership_1 \\ \vdots \\ Membership_n \end{bmatrix} \bullet [pFail_1(l) \quad \ldots \quad pFail_n(l)]$$

By repeating this analysis for each condition grade in turn, this approach can lead to the development of a family of asset-specific fragility curves, as shown in Figure A.2.

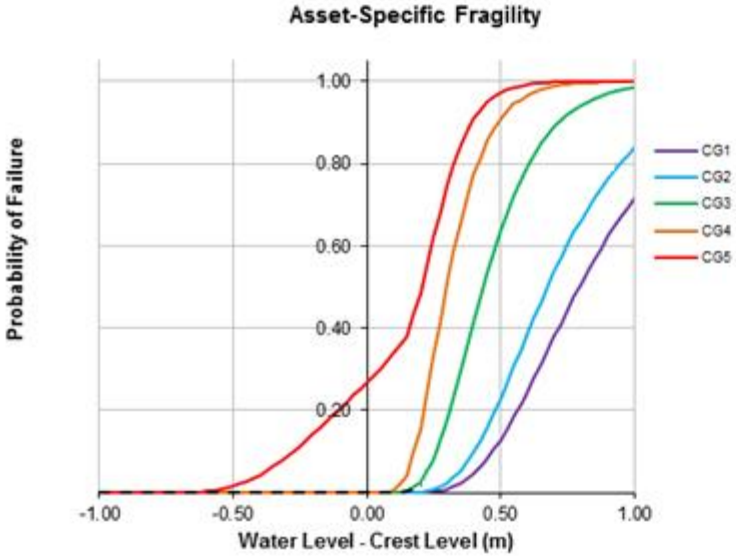

Figure A.2 Example family of asset-specific fragility curves

It is also possible to treat condition grade in the same way. Rather than select a single condition grade (1–5) to represent the current state of an asset, a weighted sum of all condition grades can be used to generate a bespoke (instantaneous) curve, which is a linear combination of all 5 custom fragility curves that represent the specific condition of the asset.

To enable the membership vector to be constructed, the key attributes of the generic fragility curves were identified and questions created to establish the likeness of the asset under investigation to the generic asset. This was achieved by reviewing the available material and extracting the most important terms for each generic fragility curve. The list of terms used is:

- Coastal
- Fluvial
- Narrow
- Wide
- Clay
- Sand
- Embankment
- Vertical
- HighGround
- Culvert
- Shingle
- Dune
- Demountable
- FrontFaceArmour
- CrestArmour

- RearFaceArmour
- SheetPile
- Sloping
- Shallow
- Steep

The terms in this list may be complementary to one another or mutually exclusive.

Each generic fragility curve was assessed against this list and all applicable terms identified. For example, RASP type 6 assets can be described using the following descriptive terms:

- Fluvial
- Wide
- Clay
- Embankment
- FrontFaceArmour

Using the descriptions provided by the user of the tool, the perceived 'likeness' to each of these attributes is established. This is used to establish the membership value using one of the 4 functions shown in Figure A.3.

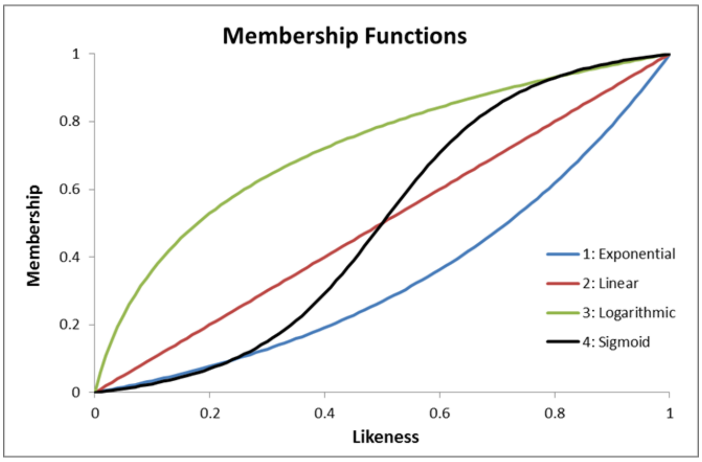

Figure A.3 Membership functions

Using the logic set out above, the more features an asset has in common with an underlying type, the higher the membership value that is assigned. The example below is for an asset with a strong likeness to one generic asset.

$$\begin{bmatrix} Membership_1 \\ Membership_2 \\ Membership_3 \\ Membership_4 \\ Membership_5 \\ Membership_6 \\ Membership_7 \\ Membership_8 \\ Membership_9 \\ Membership_{10} \\ Membership_{11} \end{bmatrix} = \begin{bmatrix} 0.0081 \\ 0.0814 \\ 0.8140 \\ 0.0000 \\ 0.0009 \\ 0.0086 \\ 0.0861 \\ 0.0002 \\ 0.0006 \\ 0.0000 \\ 0.0001 \end{bmatrix}$$

Similarly, the membership of the asset to a condition grade can be estimated by taking into account the user's perception of the asset, as well as changes in local loading condition and evidence of the asset withstanding recent large flood events, as shown in the example below.

$$\begin{bmatrix} CG_1 \\ CG_2 \\ CG_3 \\ CG_4 \\ CG_5 \end{bmatrix} = \begin{bmatrix} 0.2826 \\ 0.4214 \\ 0.2634 \\ 0.0290 \\ 0.0036 \end{bmatrix}$$

A.4 Output

The tool's output is a bespoke estimate of the probability of failure of an asset under a full range of loading conditions. This bespoke estimate aims to replace the generic fragility curves in models and analysis that need them as an input.

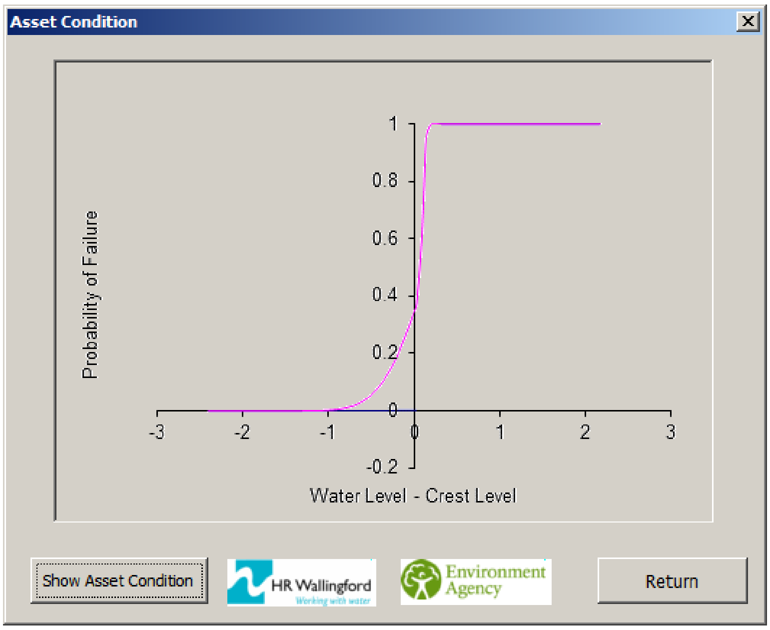

Figure A.4 Example output from the Custom Fragility Curve tool

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