flood risk management research consortium

FRMRC

IMPROVED APPROACHES TO CONDITION ASSESSMENT - VOLUME 1: PERFORMANCE-BASED VISUAL INSPECTION OF FLOOD DEFENCE ASSETS

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June 2006

FRMRC Research Report UR10

Project Web: www.floodrisk.org.uk

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Executive Summary

Work package 4.3 of the FRMRC is a *user focussed measurable outcome* intended to develop a method for visual inspection of flood defence infrastructure assets that provides an assessment of their current condition related to their likely performance. The method developed should provide a measured step towards performance based visual inspection from the currently used method. This *measured step* should balance the needs of a performance based inspection with the practical limitations and boundaries defined by the current state of systems for flood defence asset management within the UK.

There is currently a move towards performance focussed systems for the management of flood defence infrastructure which will require that asset condition is inspected in terms of its likely performance. There is a large body of research ongoing within the areas of flood risk and flood defence management. FRMRC represents a substantial body of this work along with a number of initiatives and projects being undertaken under the EA/DEFRA Joint Research & Development Programme and elsewhere.

Research was carried out to examine a number of areas directly related to the project such as performance based asset monitoring and inspection (examining best practice across a number of industries in addition to an obvious focus on flood defence management), performance models and modelling for flood defence structures and current systems employed in the management of flood defences in the UK.

The current method of visual inspection was analysed in some depth and found not to provide the required detail needed to produce an assessment of asset performance. The benefits and limitations of the current approach were also identified. This enabled a revised method to be developed that acted as a measured step forwards from the current system of inspection.

The revised visual inspection method developed is referred to as the *Condition Indexing* process as its ultimate output is a Condition Index (CI) for an asset. The process is shown in figure 1. This CI provides an assessment of the asset's likely performance in terms of its flood defence function. Condition Indexing involves the assessment of a set of *performance features* (PF) defined for an asset in terms of their current condition, the confidence associated with that condition assessment and the PFs contribution to a set of predefined failure modes (FM).

PFs were identified through the performance models, historical data and expert knowledge regarding the performance of flood defence assets. They have a number of properties such as; they must be visual, they must be gradable in terms of their condition and they must be related to potential asset failure. The FMs used were also determined using the same process.

The actual inspection of an asset requires an inspector to assign a condition grade (in the same 1-5 range as used currently) to each PF for a asset using a set of guidance flowcharts and tables provided. A confidence score associated with each PF condition is then recorded. The confidence score is a signed integer value representing the difference in value between the assigned condition and the potential condition. A confidence score of -1 would imply that the condition assigned could be inaccurate be -1 condition grade i.e. a condition grade of 3 with confidence of -1 represents potential condition of 2-3. Condition and confidence are combined with the contribution value associated with the PFs to calculate *Failure mode Index* (FI). FIs can also be assigned directly (Stage 2a in figure 1) where the a failure is self-evidently occurring and easily identifiable.

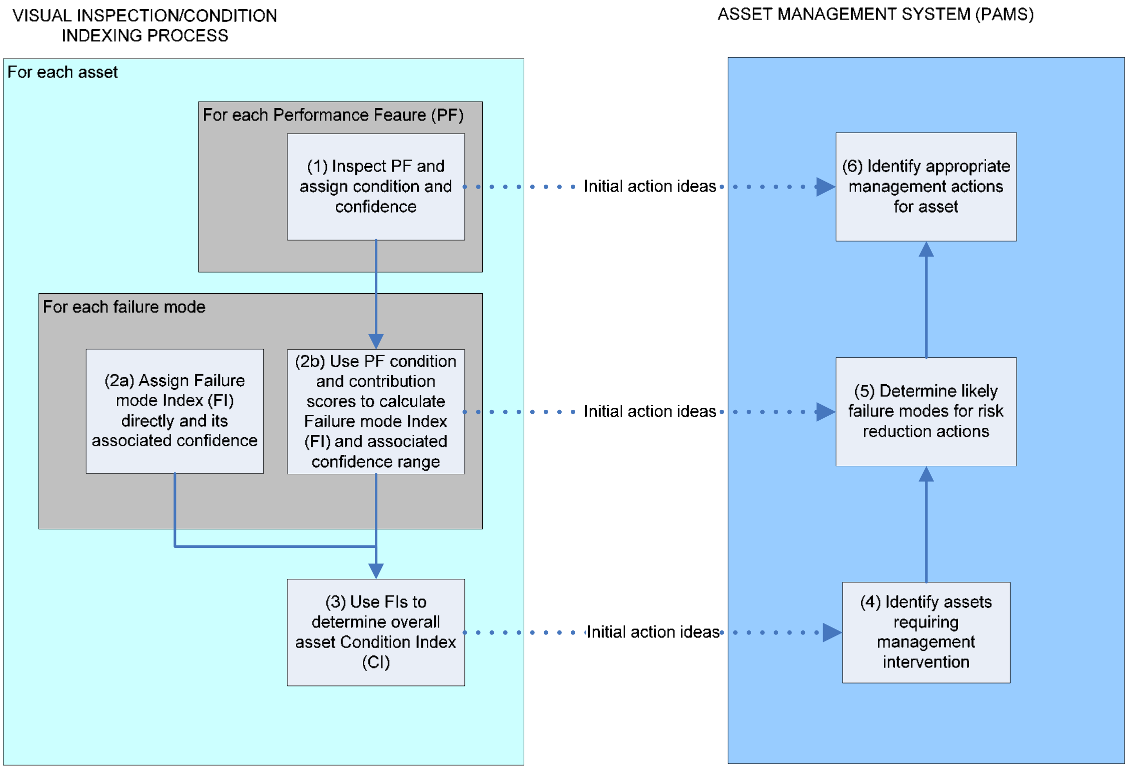

Figure 1: An overview of the Condition Indexing Process and its links to a Performance based Asset Management System (PAMS)

FIs are calculated using the set of contributions relating PFs to FMs. These contributions are developed from performance models and expert opinion and provide the link between visual findings and asset performance. All FMs have a set of contributions in the 0-1 range where the total of contributions for a FM is equal to 1.0. Equation 1 shows the calculation of FI.

$$FI(FailureMode) = \sum_{i=PerformanceFeature} Contribution(i) * Condition(i) \Big/ \sum_{i=PerformanceFeature} Contribution(i) \qquad (1)$$

A similar calculation is carried out for the maximum and minimum values of condition (determined using the confidence score associated with each PF) to produce a confidence range for each FI.

Testing of the Condition Indexing process found that CI is best determined by assigning the highest FI score (representing worst performance) to be the CI for the asset overall. The method was developed and tested over a range of major asset types and found to produce good results with a much greater level of detail than the current method of inspection. This can be used in the determination of the appropriate management response in terms of infrastructure management.

Future development of the Condition Indexing process to produce a system suitable for implementation across all asset types was discussed and the need for large scale trials of the method was identified. Initial trials are to be carried under a related project.

An ideal system for performance based visual inspection of flood defence assets was described. This system is not limited by the practical boundaries defined in terms of the measured step forwards that was an objective of the work package.

Document Details

Document History

Version	Date	Lead Authors	Institution	Joint authors	Comments
	June 2006	Gavin Long Dr Michael Mawdesley Jonathan Simm	} University of } Nottingham HR Wallingford Ltd		Final draft
			HR Wallingford Ltd HR Wallingford Ltd HR Wallingford Ltd	Foekje Buijs Paul Sayers Mike Wallis	
v1_0	June 2006	J Bushell	HR Wallingford Ltd		Formatting for publication; change of name from 'short report.doc' and assimilation of 'technical summary.doc'
End user approval: Mervyn Bramley, Defra / EA SAM Theme Advisor, 25 June 2008					

Acknowledgement

This research was performed as part of a multi-disciplinary programme undertaken by the Flood Risk Management Research Consortium. The Consortium is funded by the UK Engineering and Physical Sciences Research Council under grant GR/S76304/01, with co-funding from:

- Defra and the Environment Agency through their Joint R&D programme on Flood and Coastal Erosion Risk Management,
- UKWIR
- NERC
- The Scottish Executive
- Rivers Agency Northern Ireland

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Advisory Panel of Research Priority Area 4: Infrastructure Management

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1. Introduction

Flooding is a significant concern in terms of loss of life and property in the UK and around the world. Recent major flooding events such as those experienced in the UK in 2000 have led to an increased awareness of the need for improved systems for flood defence and flood risk management. Reports such as the Institute of Chartered Engineers *Learning to live with rivers* (ICE, 2001) have reviewed the state of UK flood risk, flood defence infrastructure and potential impacts of climate change in terms of flooding, in this instance from fluvial sources.

The increased awareness for improvements in flood risk management has lead to a number of recent initiatives in industry, government and academia in the UK. The Flood Risk Management Research Consortium (FRMRC) is one such initiative drawing together a substantial body of academic research into a number of themes related to flood risk management. Within each theme there are a number of work packages representing individual research projects. This report describes work within under the infrastructure theme (theme 4) undertaken as work package 4.3 (WP4.3) of the FRMRC programme.

Work package 4.3 is concerned with improving current methods for the visual assessment of flood defence asset condition to produce a method that more accurately reflects likely asset performance. In the UK the Environment Agency (EA) is tasked with the management of a large flood defence infrastructure of approximately 70,000 assets with a total length of over 35,000km (NADNAC, 2004). These assets are periodically inspected by qualified staff and assigned a condition grading based on their visual condition. The current method of inspection is thought to produce a inadequate assessment in terms of performance. The output of this project is classified as *user focussed measurable outcome* in terms of the output of the FRMRC.

The main objectives of the project were as follows:

1. To achieve a measured step forward in the visual inspection of flood defence assets.
2. To introduce a scientific methodology into the process wherever possible.
3. To highlight areas where the scientific methodology is lacking.
4. To provide a vision of how the inspection should be done in the future.

This report briefly describes the major elements of the research and development undertaken through WP4.3. A full report (Long & Mawdesley, 2005) describing the project in much greater depth was also produced and is advised reading for those requiring a full understanding of the project.

2. Research

A number of research areas were identified and investigated as a part of the project. These included asset management (especially in terms of asset monitoring and inspection), the performance modelling of flood defence assets and related systems used (and in development) in UK flood risk management.

Key projects related to this work were as follows:

- *Performance and Reliability of Flood and Coastal Defences (HR Wallingford, 2004a)* – This project provided key source material in terms of the potential for performance modelling of flood defence assets. It provides a review of available performance models and describes how these models can be used. It was used in the development of the link between visual inspection and asset performance
- *Condition Monitoring and Asset Management (CMAM) (Dawson, 2003; Hall 2003)* – The CMAM project covers similar topics to those investigated in WP4.3. It defines a theoretical basis for the monitoring of asset condition using a diverse set of input data. It defines assets in

terms of a hierarchy of components and sub-processes and produces a measure of asset performance which includes an assessment of the uncertainty associated with that measure.
- *USACE Condition Indexing (Mckay, Rens et al, 1999)* – This project undertaken by the US Army Corps of Engineers (USACE) represented a step forwards in the assessment of flood defences through visual inspection. It identified the key elements required to produce an assessment of asset performance through visual inspection and covered a wide range of asset types.
- *Performance based Asset Management Systems (PAMS) (HR Wallingford, 2004b)* – The PAMS project involves ongoing work developing a system for the management of flood defence infrastructure with performance as its primary focus. The output of WP4.3 will be used as the basis for the inspection of flood defence assets under PAMS. Due to this, a general understanding of PAMS and the related systems such as the National Flood and Coastal Defence Database (NFCDD), used to store flood defence asset data.
- *Risk Assessment for Strategic Planning (RASP) (HR Wallingford et al, 2002; Environment Agency 2003)* – RASP is a decision support tool used to assess likely flood risks at a number of levels of detail ranging from the national level down to individual systems of flood defences. It provides a definition of flood defence categories that was used in the development of WP4.3.

In order to produce a method representing a measured step forwards in terms of the visual inspection, a detailed understanding of the current method employed for this purpose was required. This analysis produced a number of key findings:

- Visual inspection of flood defences is performed by grading individual asset elements on a scale of 1-5 (Very Good to Very Poor). Asset elements are defined for all asset types and represent easily identifiable components across the asset cross-section.
- The current method performs well in providing a simple, assessment of asset condition in terms of its structural integrity but there is no direct link between condition and performance.
- There is a significant problem in terms of the assessment of elements in *borderline* condition. There is no formal mechanism within the method for the inspector to indicate his uncertainty regarding the assigned condition. Where this occurs at the border of two grades representing major differences in management response (grades 2-3 or grades 3-4 particularly) there is a potential for error leading to wasted resources or defence failure.
- There is no way to formally identify the specific nature of any poor condition identified within an asset element. For example, a bank slope graded at condition grade 3 could represent a slope with bare patches of vegetation, some cracking or minor slipping. This is inadequate in terms of predicting asset performance.
- Though there is a method in existence for determining overall asset condition based on its elements it is not consistently applied. This method does is based on a simple weighted calculation of surface elements and not on any scientific analysis of how these cross-sectional elements could interact to determine overall condition.
- Guidance provided to the inspector's, the Condition Assessment Manual, is a useful tool providing good coverage of asset types and including a large range of good photographic data. However, it is ambiguous, to the point of error in some instances, due to its reliance on short textual descriptions to back up this photographic data.

Analysis of performance models of flood defence structures identified a number of failure modes and processes could be assessed along with the visual indicators of failure. Current physical process models are insufficient to fully develop a system of visual inspection based on their parameters alone (many of the parameters are non-visual and require expert and/or destructive testing). Performance models can be supplemented with other sources of such as historical performance data and expert opinion in order to produce a performance based system of visual inspection.

These findings in conjunction with the analysis of the key components of other systems in use for asset monitoring and visual inspection led to the development of a revised method for visual inspection. This method is called the *Condition Indexing* process as its ultimate output is a Condition Index for the overall asset.

3. Development of a revised method for visual inspection

As the main deliverable of WP4.3 a revised method for visual inspection of flood defence assets was devised. Sections 3.1 to describes the process and its sub-processes as shown in figure 3.1. Sections 3.2 onwards provides a description of the individual elements of the Condition Indexing system in more detail.

The Condition Indexing process could be applied to any asset type. WP4.3 has produced detailed guidance for the Condition Indexing of major linear asset types (embankments, vertical wall structures and sloping revetments). This guidance is provided in the full project report (Long & Mawdesley, 2005) along with examples of how this could be expanded for other asset types.

3.1 PERFORMANCE FEATURES (PF)

Performance features are the building blocks on which the condition indexing process in based. They represent the elements of an asset that are to be inspected in order to produce the condition index. Performance features must possess a number of attributes. These are listed below in order of importance:

1. They must be related to at least one failure mode, and therefore to the performance of the asset – If the visual condition of a feature plays no role in asset performance then it should not be inspected.
2. Visible – The feature to be inspected must be easily assessed on a visual inspection. For example, many of the performance models have geotechnical parameters that cannot be observed on a visual inspection.
3. Gradable – In addition to being visually identifiable, the current condition of the feature must be able to be graded visually. There must be sufficient visual indictors related to the PF in order to assign the range of condition values associated with that PF.
4. Mutually exclusive – Ideally, PFs should be mutually exclusive. There should be no chance of mistaking the condition of one PF for another. However, this attribute can be relaxed to some degree in order to satisfy the more important attributes 1, 2 and 3 if necessary.

A PF could relate to a number of failure modes or be associated with a single failure mode. Performance features that are uniquely associated with a single failure mode are important in the differentiation of most likely failure mode and usually will have a high contribution rating linking them to that failure mode.

Performance features can apply to a single element of the asset and therefore be repeated for each element where relevant or can apply to the whole asset. The decision on whether a performance feature should be applied to individual elements or to the whole asset is dependent on the level of detail of inspection required. It is also determined by whether the location of the performance feature across the asset cross section has any differential impact on performance. It is also be possible that the combination of a given performance feature with different elements of the asset may be linked to different failure modes. An example of this is the combination of *vegetation coverage* with inner or outer slopes of an embankment would link to different failure modes.

The choice of performance feature is partly determined by what is possible to assess visually and also by the failure modes that need to be identified. Performance features must be chosen that will identify these failure modes directly or indirectly. Consistency of the method wherever possible is another factor considered in the identification of appropriate performance features. It is necessary to produce a set of performance features that balance accuracy of inspection with implementation issues such as the workload associated with inspecting an individual asset. Too large a set of performance features, though possibly producing a more accurate condition index, would increase the duration of an inspection beyond reasonable levels.

Various performance features were considered throughout the development of the method for specific asset types. A full list of performance features identified for each asset type investigated is given in the full project report (Long & Mawdesley, 2005) under the description of the measured step forwards for each asset type (sections 5.5-5.9).

3.2 CONDITION RATING

A condition rating is a numeric value representing the current condition of a performance feature determined by visual inspection.

The value range of the condition rating should allow for the inspector to discriminate condition to an appropriate level of detail between the boundary conditions, excellent (high performance) and very poor (very low or zero performance).

The choices of condition value range considered for the revised method were 1-5 and 0-100. It was felt that the broader range of values had some merit due to the increased resolution of condition values available and that a percentage based scoring system was easily understandable. The 1-5 value range is more suited to a measured step forwards as it allows the introduction of a performance based method without introducing unnecessary changes that do not provide significant benefit. It also reduces the need for significant change to the NFCDD in terms of condition ratings. There is a danger that keeping the same value range may lead to complacency in the inspection and the assignment of identical values to the current method. However it was felt that the change to inspection of performance features rather than elements and the introduction of detailed and revised guidance on the assignment of condition scores would remove this risk. Generic definitions for the revised 1-5 scores are given in table 3.1.

Table 3.1 Generic descriptions of condition by grade

Condition Grade	Description
1	Feature is in very good condition. There may be superficial damage but it has zero effect on the performance of the feature.
2	Minor damage to the feature which will result in a small loss of performance. Should not lead to failure except under extreme conditions
3	Minor but extensive or localised severe damage to the feature has reduced asset performance to a significant degree. Imminent failure is not likely under normal loading conditions.
4	Damage to the feature has caused major loss of performance. Failure could occur at any time and urgent attention is required.
5	Feature or asset is no longer able to perform its function at even a reduced level.

The generic descriptions given in table 3.1 provide a rough outline of what each condition grade represents. They could be used in conjunction to the specific asset type guidance to aid in assigning condition that is not easily identifiable using the guidance. Borderline cases would be an obvious example where the use of the table may aid the inspector judgment regarding the actual grade to assign. The confidence rating is another useful feature of the condition indexing process to deal with borderline cases (section 5.3.4). These generic descriptions of condition grade are related to the performance feature being assessed. For example, PF vegetation coverage for an embankment at condition grade 5 would represent that the vegetation is no longer performing its function i.e.

protecting the fill material from erosion. There would be little or no vegetation coverage left on the embankment slope or crest to indicate a condition grade 5. If this is compared with another PF for an embankment, Cracking and/or fissuring, then a grade 5 for this PF would indicate extensive or severe cracking of the embankment body with the cracks or fissures extending deep into the embankment. This second grade 5 indicates a far worse performance issue than the grade 5 associated with vegetation coverage but both would be classed as condition grade 5 in terms of their individual function. This difference in effect on performance is dealt with by the relative influence, or *contribution,* of the PF on a failure mode as described in the following section.

3.3 CONTRIBUTION

Contributions represent the relative influence of a performance feature on a failure mode. They are the crucial link between performance and visual inspection of condition. Contributions are pre-defined values obtained from sensitivity analysis of performance models or, in the absence of performance models, from collective expert judgment. Contributions are used to calculate the failure mode indices for an asset.

Any value scale could have been chosen to represent the contribution providing it gave enough differentiation of value to express the relative influence of all performance features or failure modes. For the sake of clarity and ease of use it was decided to use a contribution value range of 0-1 where the total of all contributions identified for each failure mode were equal to one. This ensures that all failure modes are weighted by the same total amount of contribution. It also simplifies the calculation of the failure mode indices as explained later in this chapter. Table 3.2 illustrates this point and shows a general table of contributions linking a set of performance features to a set of failure modes. In this example there are a total of *m* performance features and *n* failure modes.

Table 3.2 Performance feature contributions to failure modes

	Failure Mode				Total Contribution of PF
Performance Feature	**FM_1**	**FM_2**	**FM_3**	**FM_n**	
PF_1	C_{11}	C_{12}	C_{13}	C_{1n}	**T_1**
PF_2	C_{21}	C_{22}	C_{23}	C_{2n}	**T_2**
PF_3	C_{31}	C_{32}	C_{31}	C_{3n}	**T_3**
PF_4	C_{41}	C_{42}	C_{41}	C_{4n}	**T_4**
PF_5	C_{51}	C_{52}	C_{51}	C_{5n}	**T_5**
PF_6	C_{61}	C_{62}	C_{61}	C_{6n}	**T_6**
PF_m	C_{m1}	C_{m2}	C_{m3}	C_{mn}	**T_m**
Total	**1.0**	**1.0**	**1.0**	**1.0**	**n**

The *total contribution of PF* shown in the tables is an indicator as to the overall importance of the performance feature for the inspection process. Inspections, and the guidance and training relating to them, should focus heavily on those performance features with the highest total contribution across failure modes. There is potential for producing different tiers of inspection, for various levels of detail, using this total to rank performance features and produce streamlined inspections based on the most critical performance features. Care would need to be taken not to exclude those performance features that may only occur in one failure mode but have a relatively high contribution to that failure mode.

The main obstacle in the use of contributions is obtaining accurate contribution values that reflect actual performance. The lack of accurate and extensive performance modelling data led to the use of expert opinion to obtain contribution value sets for the development of the measured step forwards proposed by this project.

3.4 CONFIDENCE

There is wide use of confidence assessment in inspection methodologies, some of which were discussed in section 2, as it provides feedback as to the precision of the inspection. Confidence, in terms of visual inspection, refers to the inspector's assessment of the accuracy of the condition value given to a performance feature. The confidence will be affected by:

- The experience of the inspector on the specific type of asset
- The access which the inspector has to the asset
- The prevailing local weather conditions at the time of inspection
- Tidal conditions at the time of inspection (where appropriate)

In the majority of instances the likely uncertainty range should be low and be spread above **or** below the assigned condition score (but not both above and below). There may be instances where the uncertainty is high, for example when the performance feature is not inspectable due to poor visibility. The method of defining confidence values should allow for these extreme cases whilst focussing on providing the most accurate measures of uncertainty.

A number of methods that could be applied to assign confidence values to the condition score for a performance feature have been considered:

1. Quantitative measure of uncertainty. The inspector would assign a value of Low/Medium/High to the confidence. This is easy to implement and provides an indication as to the degree of uncertainty but it does not provide any indication as to the potential value range or its direction.
2. Min/Max definitions. The inspector inputs the potential minimum and maximum associated with the condition assigned. This method provides a defined measure of the potential range of the condition but requires two inputs. It may also lead to higher uncertainty results than other methods because of the tendency to always input a minimum and maximum which both differ from the condition score assigned. For example (using a 1-5 index), Condition = 3, Min = 2, Max = 4, Potential condition range = 2-4.
3. Signed Difference Value – Inspector assigns a signed (+ or -) or unsigned value to represent the likely difference between the assigned condition and actual condition. A positive score indicates that the actual value could lie in the range between the assigned value and the assigned value plus the confidence value. A negative score indicates that it lies between the assigned condition score and the condition score minus the confidence value. Unsigned values would indicate that the range of potential values lies in the range of the assigned condition index plus or minus the confidence value. For example (using a 1-5 index), condition = 2, Confidence = +1, Potential condition range = 2-3.

Option three was chosen as the method for assigning condition for the revised method. It provided the functionality necessary (unlike option one), giving both the degree and direction of the uncertainty without needing an additional data element (as with option two). The ability to assign a direction of uncertainty was deemed to be an important factor in terms of visual inspection. It was found that inspectors commonly may be uncertain regarding the condition assigned to an element or feature but they are usually confident as to the direction of this uncertainty unless it is caused by a severe lack of visual information. For example, under the current inspection method an inspector will often grade an element as lower or higher when its condition is a borderline case but they will often be aware of this uncertainty in grading. Unfortunately the current method does not allow for them to record this uncertainty formally within the bounds of the inspection methodology.

In those instances where the performance feature is not inspectable, the confidence score should **not** be used to reflect this lack of knowledge. Confidence assessment could be used to assign a condition of 3 with a confidence of +/-2 to reflect that the PFs condition could be anywhere within the 1-5 condition value range. The problem with assigning such a low measure of confidence is that the condition index produced using this method would have a very large uncertainty associated with it and the 3 assigned to condition would skew the FIs and CI's. It was deemed a better option to grade non-inspectable PFs with a zero for their condition representing that no condition was assigned for those features. The calculation of FI and CI would exclude the zero rated PF. This is further explained in the following sections.

3.5 FAILURE MODE LIKELIHOOD INDEX (FI)

The FI is a score in the same 1-5 range as the condition scores assigned to each performance feature. It is related to a specific failure mode for an asset type and is calculated using the formula below:

$$FI(FailureMode) = \sum_{i=PerformanceFeature} Contribution(i) * Condition(i) \Big/ \sum_{i=PerformanceFeature} Contribution(i) \qquad (1)$$

The nature of the visual inspection process can be highly uncertain for a variety of reasons such as poor weather conditions or restrictive access to assets when inspecting. This will inevitably lead to instances where certain performance features cannot be inspected with any degree of confidence. Any such incomplete inspection will therefore have a set of contributions totalling to less than one for one or more failure modes. In this case the calculated failure mode indices (see later section) will reflect this by the division by total contributions assessed. For example, a performance feature with a contribution of 0.5 to a failure mode is not inspectable due to poor visibility or access. The FI for that failure mode will be calculated by the summation of the other performance features inspected that contribute the other 0.5 to the total contribution of 1.0 and this will then be divided by 0.5 (the total contribution inspected) to give the FI. The fact that the FI was calculated on a reduced contribution total would be noted and may trigger the need for a re-inspection of the asset to check the omitted performance features. This could require visiting the asset at low tide, using a boat to view the asset or some other method for gaining access to the inaccessible features.

The confidence assigned to the individual PFs is used to calculate the minimum and maximum values for each FI as shown in equations (2) and (3). This produces the range of potential values for each FI. The larger this range, the greater the degree of uncertainty associated with that FI value.

$$FI(\min) = \sum_{i=PerformanceFeature} Contribution(i) * MinimumCondition(i) \Big/ \sum_{i=PerformanceFeature} Contribution(i) \qquad (2)$$

$$FI(\max) = \sum_{i=PerformanceFeature} Contribution(i) * MaximumCondition(i) \Big/ \sum_{i=PerformanceFeature} Contribution(i) \qquad (3)$$

The position of the assigned condition FI (calculated in equation 1) within the value range calculated using (2) and (3) gives an indication of the nature of the uncertainty, i.e. whether it is more likely for the condition to be better or worse than the condition assigned by the inspector. An example of the calculation of the FI along with the confidence range associated with it are given in section.

3.6 CONDITION INDEX (CI)

The Condition Index for an asset represents some indication of its overall condition based on the assessment of performance features and the calculation of Failure mode Indices associated with those performance features. In keeping with the choices made for the calculation of the FIs it was decided to use the same value range for the CI as with the other elements of the method i.e. A 1-5 range of values, with 1 representing very good performance and 5 representing low or no performance for the asset.

The calculation of the CI could be achieved using the same method used to calculate the individual FIs. This would require a set of contribution values that represented the relative likelihood of each failure mode occurring for an asset. The problem with this approach is that there is no definitive data set that could be used for the contributions at the asset type level. The accurate determination of failure mode contributions to asset performance some specific data relating to the local geography such as loading conditions, geotechnical conditions or topographical data is required. Estimations of failure mode probabilities have been researched and used in projects such as RASP (REF). These refer to a higher level of processing such as for an entire watercourse, catchment or reach and would be inappropriate for the detailed assessment of individual assets.

The use of failure mode contributions needs further research to establish whether a set of appropriate values could be determined which would be useful in terms of visual inspection of asset performance. Until this is available and for the purposes of this report a simplified version of failure mode contributions has been devised. This involves the contribution for each failure mode to be equal to each other and the total of all contributions to be equal to one (as with contributions linking failure modes and performance features).

$$Contribution_{fm} = 1.0 / n_f$$

Where $Contribution_{fm}$ is the contribution relating to a specific failure mode for an asset and n_f is the total number of failure modes relating to that asset in the condition indexing process. So, for an asset with 4 failure modes, the contribution of each failure mode is equal to 0.25.

Even if accurate measures of failure mode contributions could be established there is a more major limitation to this approach to the calculation of the asset CI. Whatever FI represents the worst performance will be the failure mode of interest in terms of actions arising from the inspection. If this is not the case, e.g. because that failure mode cannot occur or is highly unlikely for a given asset, then that failure mode should not be inspected. By applying a contribution score to each FI (which is less than 1) the performance assessment it represents will be reduced according to the size of the contribution. If a failure mode has a contribution of 0.5 and its FI is equal to 3 then its contribution to asset CI would equal 1.5. The use of contributions risks the loss of information regarding asset performance through the dilution of FI values by applying contributions to them. Due to this risk an alternative approach was devised.

The alternative method of calculating the asset CI is referred to as the *weakest FI* approach. This involves the CI being determined as being the maximum value in the set of FIs. If the FIs for an asset with four failure modes were 2.1, 3.2, 2.2 and 3.7 then the Asset CI is equal to 3.7. The problem with this approach is that it seems to ignore the FIs other than the one with the maximum value. However, it is our proposal that in terms of measuring performance at the asset level, this is precisely what should be done.

In terms of the confidence associated with the asset CI then the following methods are applied according to which approach for calculation of the CI was used. For a failure mode contribution approach the calculation of confidence is identical to the method for calculation of FI confidence. When the weakest FI approach is used then confidence associated with it is obtained by taking the maximum value in the set of both maximum and minimum FIs.

A comparison between these two approaches was undertaken and it was found that the weakest FI approach produced results that more accurately reflected the performance of assets. The FM contribution based approach produces a lower CI (representing better performance) due to the averaging out of the FI indices. This is problematic when one FI is of a high value, indicating a potential weakness in the asset, and the remaining FIs are low, indicating satisfactory or good performance. The resulting Asset CI indicates an asset in reasonable condition and likely to perform well which is misleading.

3.7 GUIDANCE AND TRAINING

Guidance and training are essential to any method of visual inspection. They are the key component in ensuring the accuracy and consistency of inspections across a wide range of inspection staff potentially working within different operational environments. The nature of the changes being proposed as a measured step towards performance based inspection are such that effective training and guidance will be critical to the success of the proposed method.

A new training programme will be needed if the method is adopted. The basic framework of the current asset inspection training could be maintained but it is felt that the training course duration would have to increase to cover the increased complexity of condition indexing in relation to the current inspection method. The inclusion of failure modes and the differences in inspection across asset types would be elements that would require additional training to ensure the knowledge is accurately passed on to the inspection staff. The actual development of such a training programme lies outside the scope of this report and as such will not be further mentioned.

The guidance needed to assign condition to performance features accurately and consistently is a key requirement of the condition indexing process. The current guidance manual provided to inspection staff (Glennie et al, 1991) would be insufficient for the assessment of condition under the revised method even if it were adapted to suit performance features as opposed to defence elements. Some of the knowledge it contains is still useful in assigning condition to the performance features and has been used in the development of appropriate guidance for the revised method of visual inspection.

A number of mechanisms for providing guidance were investigated as a part of this project. Brief descriptions of these are listed below:

- Condition grade descriptions and images - As used in the current method of visual inspection for UK flood defences. These provide a simple method for assessment of condition but are insufficient for the more complex system of inspection proposed if consistency of inspection is to be kept high.
- Flowcharts – Provide a highly structured mechanism for assigning condition and are used for visual inspection of assets within a number of asset management systems. The increased structure and fixed pathways in the flowchart ensures greater consistency of assessment than a textual description, which suffers from the ambiguous nature of natural language. Flowcharts display the process of condition assessment across all condition grades within a single chart. This allows the inspector to understand the differences between the grades of condition more easily. The production of flowcharts is a more complex process than a text description and must be extensively trialled to spot any errors and/or omissions. The rigid structure of the flowchart can also be a limitation as it will be impossible to include every possible situation and combination of factors that may be found on site.
- Checklists – The use of checklists is a common approach to visual inspection in many industries. The USACE Condition Indexing system (McKay, Rens et al, 1999) commonly employs checklists in the recording of asset condition. A checklist is a simple method for ensuring that the data needed for a visual inspection is consistently collected following a fixed procedure. A checklist will typically require the inspector to provide a series of answers to fixed questions that build up to provide the condition assessment required. These questions will involve simple *yes/no* type responses or for the inspector to categorise certain features or findings on site. This method of guidance is a good way to ensure consistency of inspection but can require the assessment and recording of a large amount of data therefore increasing the duration of the inspection process. It also requires the checklists used to be fairly extensive and detailed in their content. There is a danger that any findings from the inspection that do not fit into the checklist may be ignored.

The guidance method chosen for use in the condition indexing process is flowchart based. This is felt to provide the structure needed to ensure consistency of inspection and, in addition is a simple to use method that does not require too much additional input from the inspector unlike checklists. It is noted that there may be some performance features that would not be readily assessed using this approach and that the other guidance methods would be applied where they were necessary.

Flowcharts were designed using some general principles applied to all charts for greater ease of use. The definitions of *minor* and *severe* referred to commonly in the charts refer to the following general description:

- *Minor* – The item being assessed is only visible to a close and detailed inspection of the performance feature. For example, a minor misalignment of the crest of a vertical wall would only be visible if the inspector were to closely examine the crest looking along it and comparing it with other wall sections.
- *Severe* – The item begin assessed would be easily visible under a cursory inspection. Using the previous example for the crest of a vertical wall, a severe misalignment would be obvious to the inspector as he approached the asset. It would not require close inspection to identify it and would be visible to a non-expert or member of the public.

To reduce ambiguity, notes have been attached to those charts where it was felt that the decisions to be made could be unclear. These notes will describe the nature of each response type and what visual findings would map to each response type. Photographic data was not included in the flowcharts developed for use in the pilot trial of the method. The addition of photographic data to the relevant sections and decision boxes of the charts would provide additional guidance and help in the condition assessment process.

An example of the guidance flowcharts used in the Condition Indexing process is shown in figures 3.2. A full set of guidance charts and tables in given along with explanations of each in the full report related to this work package (Long & Mawdesley, 2005).

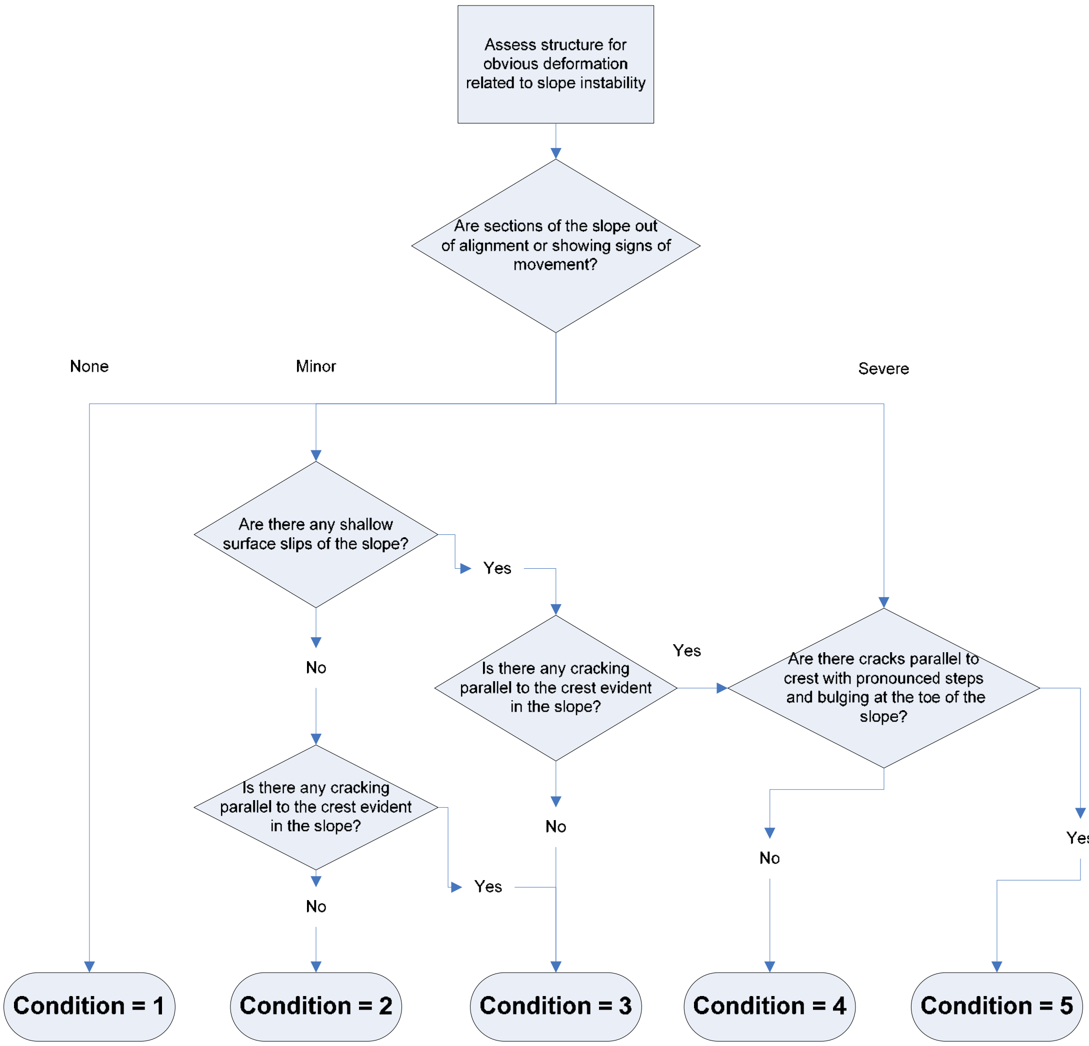

Figure 3.2 Flowchart to assess any deformation of embankment cross section caused by slope instability

3.8 THE CONDITION INDEXING PROCESS

There are a number of actions that make up the condition indexing process as shown in figure 3.1. These will now be described in more depth to give a thorough understanding of the overall process:

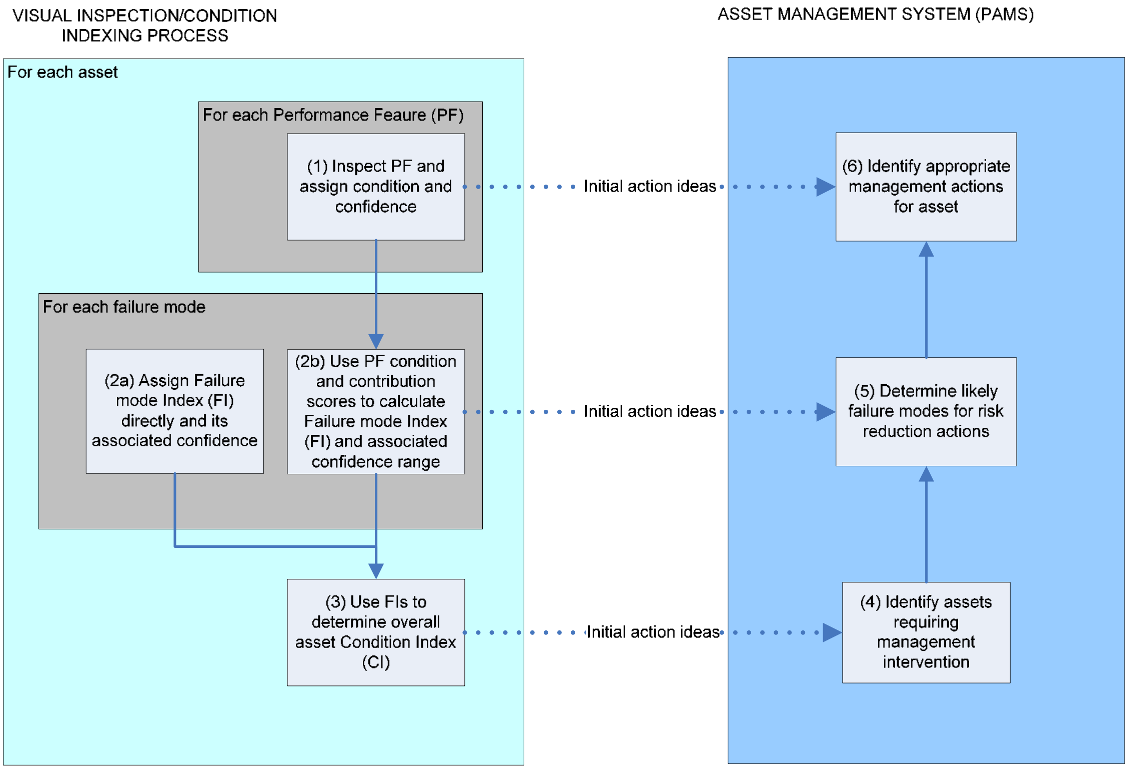

Figure 3.1 An overview of the Condition Indexing Process and its links to a Performance based Asset Management System (PAMS)

Pre-Inspection – Data gathering and inspection planning

Prior to the actual inspection, an inspector should obtain all the relevant data relating to the sites to be inspected. This could include previous asset inspection records, local geography and asset locations, design records, local geotechnical information, asset topography and the standards of protection afforded by the assets (i.e. their performance specification). Much, if not all, of this data should be obtainable from the NFCDD. The exact data requirements will also be determined partially by the inspector's experience and their knowledge of the assets to be inspected. Previous inspection data should always be examined to provide a comparison with the inspection to be carried out, to observe any changes to the asset occurring over time and to highlight any known points of weakness for more detailed inspection.

Step 1 – Assessment of the performance features

This step of the process represents the actual on-site inspection of the asset and is shown as process (1) in figure 3.1. The inspector performs a detailed observation of the asset and assigns condition and the associated confidence scores to each PF in turn. If a particular failure mode is self evidently occurring or is known to dominate for a given asset then the inspector has the option to ignore this step and move straight onto step 2 taking the 2(a) option. This allows the inspector to override the condition indexing process where there is an obvious failure occurring. This eliminates wasted inspection time in the assessment of performance features that will not be needed to identify the asset CI.

As with the current inspection method, the inspector should also be encourage to add their recommendations or notes onto the inspection record. This could be additional detail regarding the condition or confidence assigned to a PF, potential actions or maintenance work that is required or notes regarding the conditions under which the inspection was carried out.

Step 2 Calculation of the failure mode indices

Step 2 involves the calculation of the FI scores for an asset. This step can be achieved in two ways:

- 2(a) Override – Where a failure mode is self evidently dominating the inspector can assign a condition score directly for the FI thereby eliminating the unnecessary assessment of PFs for an obviously occurring failure of the asset.
- 2(b) Standard – Calculation of the FIs from the assessed PFs using contributions scores and the formulae given in section 3.6.

The 2(a) and 2(b) refer to figure 3.1. Override should only be used where the nature of the failure occurring is obvious. This could be due to the inspector's detailed knowledge of the asset, data obtained in the pre-inspection stage and confirmed on site or the imminent and self evident failure of an asset. For example, if the inspector arrived at a vertical wall structure to find the wall leaning into the river at an angle with obvious and severe movement of the structure having occurred then the inspector could ignore the assessment of individual PFs and assign a condition grade 5 to the relevant failure mode (in this case, overturning). Another example would be an embankment which was well known to be prone to piping failures due to the soil of its construction[1]. When inspecting this asset, the inspector may look for any other evidence of damage or deterioration not related to the piping and, if none is found then inspector could assign a condition grade directly to the piping FI corresponding to the current condition of the asset.

Override is a useful technique to reduce the overhead of the condition indexing process where it is not relevant to the on-site findings and asset data. When the inspector overrides assessment of PFs they should note the reasons for this in their inspection record.

The standard approach to the calculation of the FIs could be performed during or post inspection. It could also be easily automated using a computer application or spreadsheet.

Step 3 Calculation of the asset Condition Index

This can be done on site or post inspection and be easily automated as with step 2. Potential methods for the calculation are discussed in section 3.7.

Post Inspection – analysis of results

Once the asset CI has been calculated then the condition indexing process is complete for that asset. The asset management system (PAMS, IFRM, FDMS) will then be used to analyse the inspection results and determine an appropriate course of action.

4. A worked example of the Condition Indexing process

The following example is taken from the full project report (Long & Mawdesley, 2005) which contains a full set of examples using assets whose condition is well understood as they are used in the current asset inspection training programme. This asset knowledge, and photographic data, is provided thanks to Middlesex University's Flood Hazard Research Centre (FHRC) and John Chatterton of John Chatterton Associates who provided invaluable aid and assistance to the project.

[1] An embankment of this type was noted on the tidal section of the river Trent during the research phase of this project.

Figure 4.1 Overview of the composite structure.

Figure 4.2 Concrete crest wall forming third component of composite asset.

4.1 ASSET DESCRIPTION

The asset shown in figure 4.1 is a composite structure consisting of three separate asset types. At the side of the channel there is a small sheet pile wall structure. Behind this is the embankment that can be clearly seen in the photograph. At the rear of the crest is a concrete wall structure which is shown in detail in figure 4.2 . This acts as a crest wall to protect the properties behind the embankment.

Visual inspection of the asset shows that there are some underlying problems present within the embankment and crest wall. Figure 4.3 and 4.4 show examples of poor condition identified on site. Movement and cracking of the slope and crest of the embankment were noticeably apparent under visual inspection. The crest wall showed significant loss of joint material and some misalignment at the joints.

Figure 4.3 Close up of damage to crest of the embankment component

Figure 4.4 Close of damaged joints in crest wall

Due to the nature of this composite asset, it will be assessed as three separate asset types under the condition indexing process.

4.2 STEP 1 - ASSESSMENT OF PERFORMANCE FEATURES

The three components that form example 3 will be named as follows:

- 3a – A cantilevered sheet pile wall protecting the channel side of the embankment
- 3b – An earth embankment with an asphalt path on the crest
- 3c – A concrete crest wall structure protecting local residential buildings under high loading conditions.

Tables 4.1, 4.2 and 4.3 show the performance features assessed under the condition indexing process for 3a, 3b and 3c respectively.

Table 4.1 Performance feature assessment for asset component 3a (sheet pile wall)

Performance Features	Condition	Confidence	Condition Max	Condition Min
1. Obvious deformation of structure and/or surroundings (rotational slip)	1	0	1	1
2. Obvious deformation of structure and/or surroundings (rotation)	1	0	1	1
3. Obvious deformation of structure and/or surroundings (backfill washout)	1	0	1	1
4. Toe scouring/undermining	1	+2	3	1
5. Condition of wall material	1	+1	2	1
6. State of the joints	1	+1	2	1
7. Third party interference with load or resistance	1	0	1	1
8.Animal infestation in ground around structure	2	0	2	2
9.Seepage through structure, behind or in front of structure	1	0	1	1
10. Presence of foreign objects	1	0	1	1

Table 4.2 Performance feature assessment for asset component 3b (embankment)

Performance Features	Condition	Confidence	Condition Max	Condition Min
1. Animal burrowing/vermin infestation	1	0	1	1
2. Foreign objects in the crest or rear slope concentrating the erosion process	1	0	1	1
3. Cracking and /or fissuring	4	+1	5	4
4. Third party damage (cattle, vehicles etc)	1	0	1	1
5. Direct evidence of seepage or piping	1	0	1	1
6. Visible deformation of cross-section caused by slope instability	4	+1	5	4
7. Erosion of cross section	1	0	1	1
8. Vegetation condition (outer slope)	1	+1	2	1

Table 4.3 Performance feature assessment for asset component 3c (gravity crest wall)

Performance Features	Condition	Confidence	Condition Max	Condition Min
1. Obvious deformation of structure and/or surroundings (horizontal sliding)	2	0	2	2
2. Obvious deformation of structure and/or surroundings (rotational slip)	1	0	1	1
3. Obvious deformation of structure and/or surroundings (overturning)	1	0	1	1
4. Obvious deformation of structure and/or surroundings (bearing capacity)	2	0	2	2
5. Obvious deformation of structure and/or surroundings (backfill washout)	0	0	0	0
6. Toe scouring/undermining	2	-1	2	1
7. Condition of wall material	2	0	2	2
8. State of the joints	5	-1	5	4
9. Third party interference with load or resistance	1	0	1	1
10.Animal infestation in ground around structure	1	0	1	1
11.Seepage through structure, behind or in front of structure	2	0	2	2
12. Presence of foreign objects	1	0	1	1

4.3 STEP 2 - CALCULATION OF FAILURE MODE INDICES

Tables 4.4, 4.5 and 4.6 shows the calculated FIs for components 3a, 3b and 3c of example 3 respectively.

Table 4.4 Calculated FI values with associated confidence range values for asset 3a (sheet pile wall)

	Rotational Slip	Rotation	Collapse	Backfill Washout
Assigned FI	1.00	1.00	1.00	1.20
Minimum FI	1.00	1.00	1.00	1.20
Maximum FI	1.40	1.80	1.70	1.40

Table 4.5 Calculated FI values with associated confidence range values for asset 3b (embankment)

	Slope Instability	Piping	Backfill washout	Overtopping leading to breach
Assigned FI	3.25	1.60	1.75	1.00
Minimum FI	3.25	1.60	1.40	1.00
Maximum FI	4.00	1.80	2.00	1.20

Table 4.6 Calculated FI values with associated confidence range values for asset 3c (gravity crest wall)

	Horizontal Sliding	Rotational slip	Overturning	Bearing Capacity	Collapse
Assigned FI	2.30	1.30	2.00	1.70	2.70
Minimum FI	1.90	1.10	1.60	1.70	2.40
Maximum FI	2.30	1.30	2.00	1.70	2.70

4.4 STEP 3 - CALCULATION OF CONDITION INDEX

Table 4.7 Asset CI score for composite defence (example 3) including component CIs

Asset/Component	Minimum confidence CI	Asset CI	Maximum confidence CI
Component 3a (cantilevered sheet pile wall)	1.20	**1.20**	1.80
Component 3b (earth embankment)	3.25	**3.25**	4.00
Component 3c (gravity crest wall – concrete)	2.40	**2.70**	2.70
Overall Asset (example 3) comprising 3a, 3b & 3c	**3.25**	**3.25**	**4.00**

In this example an overall asset CI for the whole composite asset has been calculated using the *weakest link* approach used to calculate the individual component asset CIs. The method of using *FM contributions* to calculate Asset CI as used in the previous two examples has not been used in this case. Problems with the approach were discussed in the previous two examples and it is felt to be an inappropriate method unless some scientific basis for establishment of such contribution values could be employed.

4.5 COMPARISON WITH EXISTING INSPECTION METHOD

Figure 4.5 shows the cross section diagram of the composite asset (example 3) used by the current inspection method. The individual elements inspected are shown in the diagram.

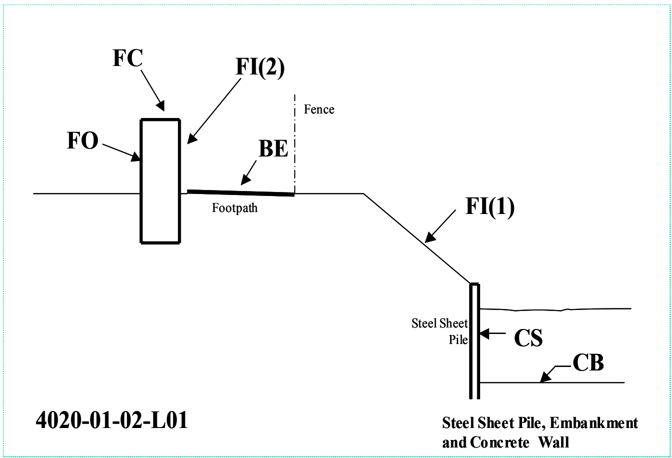

Figure 4.5 Cross section of asset showing the elements assessed under the existing visual inspection method

The condition grades assigned to the individual elements under the current method are shown in table 4.8. There is agreement with condition indexing process with poor condition assigned to the embankment and crest wall in particular.

Table 4.8 Visual inspection results for example 3 under the current method

Defence Element	Condition Grade
CS	2
FI1	4
BE	4
FI2	4
FC	4
FO	4

The current method does not provide the same wealth of detail regarding the potential range of condition and does not indicate the specific weaknesses other than identifying the weaker elements of the asset. The condition indexing process provides potential failure modes that are likely (by assessment of the individual FIs) and highlights the specific weaknesses and defects in the asset such as cracking of the embankment, deformation of the embankment and very poor joints in the crest wall (through assessment of the PFs). Under the current inspection method, the inspector would have to add recommendations to indicate the specific areas of weakness and their nature.

5. Conclusions and further work

Key conclusions of this research project are as follows:

- There is a large body of work related to the performance of flood defence assets. Much of this work has been developed from a geotechnical or hydrological viewpoint and there is often no direct link between the parameters of the various physical performance models available and the visible surface features of an asset. The models often require a great deal of accurate information regarding asset geometry which may not be available to a simple visual inspection.
- There are a number of areas where performance modelling of flood defence assets is not sufficiently detailed to provide the basis for performance assessment through visual inspection.
- By combining physical and statistical performance models with expert opinion it is possible to generate a set of *performance features* that are visually assessable and are directly or indirectly linked to performance. The relative influence or *contribution* of performance features on a set of failure modes for an asset can be generated through the same combination of models.
- The current condition of a *performance feature* and the confidence associated with that assessment can be combined with its *contribution* to failure to generate a *failure mode index* that is related to the likelihood of a failure mode occurring.
- Once a set of failure mode indices have been generated, it can be used to determine the overall *condition index* for an asset which is related to asset performance and its likelihood of failure.
- A method has been developed based on the findings of the research which represents a measured step towards a performance based method for visual inspection. The method of *condition indexing* produced balances the needs for performance based assessment with the practical limitations of the visual inspection of a large geographically dispersed set of infrastructure.
- The process of Condition Indexing provides a greater level of detail in terms of its output than the current inspection method. It enables the asset manager to identify the specific failure mode most likely to occur and determine the specific causes related to potential failure. Under the current system of visual inspection the asset manager would only be able to identify the weaker elements of the asset and would not know the specific type of weakness (e.g. cracking,

instability, third party interference). This represents a major improvement in visual inspection that will integrate well with the needs of the PAMS system currently in development.

- The increased level of detail produced by the Condition Indexing process also requires additional overheads in terms of the complexity and duration of the visual inspection process. Care has been taken to avoid a significant increase but some increase is an unavoidable price for the extra level of detail produced. It is thought that further refinement of the method and experience in its use should reduce any increased inspection overhead substantially.
- There is a large degree of uncertainty associated with many of the physical performance models currently available. Further and ongoing research into flood defence performance should help to reduce this uncertainty and produce better models of performance.
- Extensive trialling of the condition indexing method will be required to assess its potential for assessment of asset condition and performance. Some trials are being undertaken under the Thames Estuary 2100 project and as a part of phase 2 of the PAMS project. Further trials across a variety of locations are urged to fully test the method with practitioners.

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