Performance based inspection of flood defence infrastructure: Integrating visual inspection and quantitative survey measurements
Performance based inspection of flood defence infrastructure: Integrating visual inspection and quantitative survey measurements
FRMRC Research Report SWP4.2

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Statement of Use
This report is intended to be used by asset managers, consultants and researchers working on flood defence asset management. The guidance is focused on research in the UK although the findings are relevant internationally and in related industries managing large infrastructure assets.

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Summary

Monitoring and condition assessment underpin an infrastructure asset management programme. These provide the basic information on which to base asset management planning. Qualitative expert judgment, based on visual inspection, is a major input to this performance based assessment. However, a contradiction exists in that the performance models for infrastructure assets, and flood defence assets in particular, require quantitative assessments of performance features.

Work done under the initial phase of the Flood Risk Management Research Consortium (FRMRC) devised a measured step towards performance based visual inspection (WP4.3) and investigated state of the art methods for acquiring quantitative data types for use in flood risk mapping (WP5.1). Drawing on the results obtained from these two previous studies, it was noted that there was an opportunity to combine aspects of each and examine how existing quantitative assessment might be improved, and/or new quantitative assessment achieved to supplement current performance based asset inspection.

This work investigates the types of quantitative assessment that are relevant within the context of flood defence asset management. It focuses on major types of linear flood defence, highlights performance features that would benefit from quantitative assessment and identifies methods for this data through remote measurement, continuous monitoring and detailed asset inspections. Methods proposed range from inexpensive additions to the visual inspection process, aerial surveys employing specialist equipment and the installation of state of the art sensor arrays and cameras on site. The benefits and limitations of the various methods and approaches are discussed in depth for each of the main types of linear flood defence asset.

Asset surface geometry, and any variations to it occurring over time, was identified as an area where quantitative assessment can be used to improve the assessment of performance for all assets. LiDAR and Kinematic GPS were identified as methods that could provide such assessment to a sufficient level of accuracy and be integrated within the overall flood management programme. These two methods were examined in detail and their potential for quantitative assessment and the logistics of their use in flood defence monitoring were assessed.

Site-based trials, computer simulation and a number of case studies are used to strengthen the findings of the research and to highlight aspects of particular interest and relevance from the perspective of flood defence monitoring and assessment.

End-user guidance, together with generic conclusions and recommendations covering the range of topics relevant to the aims of the project are given. These include a range of potential changes that could be carried out immediately and those achievable in the short to medium term. It discusses both the theoretical potential and the practical implications of remote measurement, continuous monitoring and detailed asset inspections.
Table of Contents

FRMRC Research Report SWP4.2 ................................................................. 1
Project Website: www.floodrisk.org.uk .................................................... 1
Document Details ...................................................................................... 1
Document History ....................................................................................... 1
Statement of Use ........................................................................................ 1
Acknowledgements ................................................................................... i
Disclaimer .................................................................................................. ii
Summary ..................................................................................................... iii

Table of Contents ....................................................................................... iv
1 Introduction ................................................................................................ 1
  1.1 Background and overview ................................................................. 1
  1.2 Aims and objectives .......................................................................... 1
  1.3 Scope and deliverables ....................................................................... 2
  1.4 Report structure ................................................................................ 2
2 General principles and methodologies ..................................................... 4
  2.1 Introduction ....................................................................................... 4
  2.2 Objectives of asset monitoring ......................................................... 4
    2.2.1 Ascertain the current condition of the asset ......................... 4
    2.2.2 Assist in predicting the likely performance of the asset compared to its specification ......................................................... 5
    2.2.3 Ensure that the infrastructure system as a whole functions as required ... 5
    2.2.4 Reduce or optimise maintenance procedures .................. 5
  2.3 Visual inspection ............................................................................... 5
  2.4 Remote measurement ....................................................................... 6
    2.4.1 Light Detecting And Ranging (LiDAR) ................................. 7
    2.4.2 Photogrammetry ................................................................... 8
    2.4.3 Radar based sensing (SAR, InSAR, ASAR) ...................... 9
    2.4.4 Sonar and wide swathe bathymetry ................................ 10
  2.5 Fixed point continuous monitoring .................................................. 11
    2.5.1 Motion and positional sensors .......................................... 11
    2.5.2 Fixed cameras ...................................................................... 13
    2.5.3 Moisture detector ............................................................... 13
    2.5.4 Micro-Electro-Mechanical Systems (MEMS) ..................... 14
    2.5.5 Integrated sensor arrays ..................................................... 14
  2.6 Detailed survey ................................................................................. 14
    2.6.1 Detailed topographic survey ........................................... 15
    2.6.2 Non Destructive Testing (NDT) methods .......................... 15
    2.6.3 Invasive testing and geotechnical surveys ...................... 15
  2.7 Detailed inspection .......................................................................... 16
  2.8 Spatial scales of monitoring and inspection .................................... 17
    2.8.1 Catchment or regional level ............................................ 17
    2.8.2 Reach/sub-reach level .................................................... 20
    2.8.3 Asset level ......................................................................... 21
  2.9 Quantitative assessment of infrastructure assets ................................ 22
    2.9.1 Absolute versus relative assessment .................................. 22
    2.9.2 Accuracy and precision of assessment ............................... 22
  3 Earth embankments ......................................................................... 24

Work Package 4.2 Final Report 11 September 2012
Integrating visual inspection and quantitative survey measurements

Performance based inspection of flood defence infrastructure:
FRMRC Research Report SWP4.2

3.1 Introduction ................................................................................................................. 24
3.2 Embankment performance and failure ........................................................................ 24
  3.2.1 Structure and performance of earth embankments for flood defence ... 24
  3.2.2 Failure modes, deterioration processes and their visual indicators ... 25
3.3 Surface condition appraisal and monitoring ................................................................. 26
  3.3.1 Crest height ........................................................................................................... 28
  3.3.2 Cracking ............................................................................................................... 31
  3.3.3 Slumping/rutting .................................................................................................. 32
  3.3.4 Heaving / uplift .................................................................................................... 34
  3.3.5 Slipping / sliding .................................................................................................. 34
  3.3.6 Deterioration of surface protection .................................................................... 35
  3.3.7 Large scale settlement or movement .................................................................... 36
3.4 Subsurface failure indicators and monitoring ............................................................... 37
  3.4.1 Presence of internal voids ..................................................................................... 37
  3.4.2 Soil permeability .................................................................................................. 38
  3.4.3 Internal seepage .................................................................................................... 39
4 Vertical walls (Gravity) .................................................................................................... 40
  4.1 Gravity walls – performance, deterioration and failure ............................................. 40
    4.1.1 Failure modes, deterioration processes and their visual indicators ............... 40
  4.2 Surface condition appraisal and monitoring options ............................................... 41
    4.2.1 Remote measurement ......................................................................................... 42
    4.2.2 Continuous monitoring ....................................................................................... 44
    4.2.3 Detailed inspection ............................................................................................... 45
  4.3 Subsurface condition appraisal and monitoring ......................................................... 46
5 Vertical walls (Sheet pile) .................................................................................................. 48
  5.1 Sheet pile walls – performance, deterioration and failure .......................................... 48
    5.1.1 Failure modes, deterioration processes and their visual indicators ............... 49
  5.2 Surface condition appraisal and monitoring ............................................................... 49
    5.2.1 Remote measurement ......................................................................................... 49
    5.2.2 Continuous monitoring ....................................................................................... 50
    5.2.3 Detailed inspection ............................................................................................... 50
  5.3 Subsurface condition appraisal and monitoring ......................................................... 52
6 Revetment/ Slope protection against erosion and other types of flood defence asset ... 53
  6.1 Revetment performance, deterioration and failure ....................................................... 53
    6.1.1 Revetment types ................................................................................................... 53
    6.1.2 Failure modes, deterioration processes and indicators ...................................... 54
  6.2 Surface condition appraisal and monitoring for revetment ....................................... 55
    6.2.1 Remote measurement ......................................................................................... 55
    6.2.2 Continuous monitoring ....................................................................................... 56
    6.2.3 Detailed inspection ............................................................................................... 57
  6.3 Subsurface condition appraisal and monitoring for revetment ................................ 57
  6.4 Miscellaneous flood defence asset types .................................................................. 57
    6.4.1 Culverts and trash screens .................................................................................. 57
    6.4.2 Groynes ............................................................................................................... 59
    6.4.3 Outfalls ................................................................................................................ 59
    6.4.4 Gabions and reno mattresses ............................................................................... 60
    6.4.5 Natural coastal defences ..................................................................................... 61
7 Case studies and trials ..................................................................................................... 63
  7.1 Computer based simulation of LiDAR ......................................................................... 63
7.2 Analysis of airborne remote measurement data ........................................67
  7.2.1 Case Study 1 – Low resolution datasets ........................................67
  7.2.2 Case Study 2 – Intermediate resolution datasets ..........................68
  7.2.3 Case Study 3 – High resolution datasets ........................................70
7.3 Kinematic GPS for assessing asset geometry ........................................71
  7.3.1 Trial 1 – Wheel mounted GPS .........................................................71
  7.3.2 Trial 2 - Backpack mounted GPS ....................................................75
  7.3.3 Trial 3 – Backpack mounted GPS profiling poor condition coastal
   embankment .............................................................................................77
  7.3.4 Fault profiling with RTK GPS ............................................................78
7.4 Inferring geotechnical conditions from aerial remote sensed data ..........80
8 Conclusions .................................................................................................82
  8.1 Quantitative assessment and performance based inspection ..............82
  8.2 Remote measurement ............................................................................82
  8.3 Continuous Monitoring ........................................................................85
  8.4 Detailed asset inspection .......................................................................86
  8.5 Areas for further research .....................................................................87
  8.6 Future developments in asset monitoring and inspection ..................88
   8.6.1 Technical advances .........................................................................88
   8.6.2 Social and environmental change ..................................................90
9 Recommendations .........................................................................................92
  9.1 Changes to the visual inspection process ............................................92
  9.2 The introduction of a detailed asset inspection process .......................92
  9.3 Employing remote sensed data in asset monitoring ............................95
  9.4 Continuous monitoring of critical infrastructure ...............................96
  9.5 Data management, application and retention .......................................97
References .......................................................................................................100
Appendices ......................................................................................................103
  A Embankment LiDAR Simulator ...............................................................104
  B Analysis of LiDAR datasets ....................................................................107
  C Trial of low tech monitoring solutions ..................................................110
  D Case Study – Environment Agency trash screen camera trial ...............116
  E TE2100 Project – Combining remote measurement and asset inspection...119
  F Crest profile data from Kinematic GPS trials ........................................125
  G Summary of potential technologies and methodologies for flood defence
   asset monitoring ........................................................................................127
1 Introduction

1.1 Background and overview

Flooding and the damage caused by it to people, property, environment and the economy is a major concern. The effects and impact of flooding are likely to grow due to increased pressure on land use and increased rainfall events and sea level rise caused by climate change. Effective flood risk management and flood alleviation programmes are essential to mitigate the effects of flooding in the UK and internationally. Recent flooding events in the UK (e.g. Boscastle, 2004; Carlisle, 2005; Hull, 2007; Gloucestershire 2007) and internationally (e.g. New Orleans, 2005; France, 2010; Eastern Europe, 2010) highlight its disastrous and lethal effects.

Soft engineering solutions to make space for water and reduce the risk of damage caused by flooding are an essential and growing aspect of flood risk management but the need to build, monitor and maintain hard defences is an element of flood risk management that will continue to be both necessary and critical in the alleviation of flood risk.

In the UK, the Environment Agency (EA) manages a huge network of infrastructure assets used to protect against the effects of flooding. A large proportion of these are linear defences such as embankments, walls and sloped revetments. The need for accurate data on the condition and likely performance of these assets under loading is critical to their effective management. Previous work under the initial phase of the Flood Risk Management Research Consortium (FRMRC1) investigated methods for performance based visual inspection of linear defences (Long et al, 2006). A method was devised that represented a measured step towards performance based visual inspection from the existing visual inspection regime. However, it was noted that quantitative assessment of key indicators was needed to model more fully their likely performance and a purely visual inspection is limited in its ability to produce quantitative assessments accurately.

This report describes a project undertaken in the second phase of FRMRC (FRMRC2) to expand upon this previous work and combine it with results obtained from another FRMRC1 project investigating the state of the art in quantitative assessment of terrain and surface features (Smith et al, 2006). The FRMRC2 project investigated options for the quantitative assessment of those key linear defence types agreed with the project steering group. These include earth embankments, vertical walls and sloped revetment structures.

1.2 Aims and objectives

As with any research project the aims and objectives of the work package evolved and were refined in reaction to findings of the research and feedback obtained from industry and the project steering group. The initially proposed aim for the project as outlined in the project inception report was:
To develop (to proof of concept) an approach to condition assessment that provides an increased accuracy over purely visual inspection without significant overall increases in assessment cost by the inclusion of remotely sensed datasets and quantitative survey data.

In order to achieve the overall aim of the project, the following sub-objectives were defined:

- Investigate the degree to which quantitative measurements can be usefully integrated into the operational process of visual inspection of flood defence assets.
- Devise a methodology for a more detailed inspection of flood defence assets that incorporates quantitative assessment methods and provides a more accurate assessment of condition feeding into better assessment of likely performance under loading.
- Identify the potential and utility of airborne remote measurement methods such as LiDAR and photography for asset monitoring.
- Investigate the potential for continuous monitoring methods via electronic or mechanical sensors and telemetry

1.3 Scope and deliverables

As can be seen from the aim of the work outlined in section 1.2, the scope of this project is potentially very broad. In order to reduce this to a manageable level for the resources available to the project it was necessary to restrict and focus the project in a number of ways:

- No detailed consideration of methods requiring expert operation and interpretation are included. These methods are to be left within the realm of the external consultant.
- Invasive methods and techniques are not deemed to be within the context of this work. Some minor modification of an asset to include instrumentation of measuring equipment is however acceptable.
- Wherever pertinent recent studies existed they were used rather than repeating the experimental work
- This report focuses on monitoring and inspection methods that have the potential both technically and practically to be used within the context of flood defence asset management in the UK.

1.4 Report structure

The report is structured as follows:

- Chapter 2 – describes the fundamental principles and concepts related to infrastructure asset monitoring, with emphasis on those issues most relevant to flood defence assets. This includes some general discussion of the objectives of asset monitoring procedures, the definition and description of various types of monitoring and inspection methods and the potential for monitoring assets at a range of spatial scales.
- Chapter 3 – is concerned with the earth embankment type of flood defence that is the principal form of linear flood defence in the UK. It describes embankment performance and most common modes of failure. Surface and
sub-surface indicators of failure are given along with examples of how these could be assessed quantitatively.

- Chapter 4 – is concerned with the vertical wall types structures and specifically gravity types of wall that rely on their mass as the means to perform their flood defence role. Their performance and most common modes of failure are described. Surface and sub-surface indicators of failure are given along with examples of how these could be assessed quantitatively.

- Chapter 5 – is concerned with the vertical wall types structures and specifically sheet pile types of wall that rely on their anchor rods, ties or a cantilevered design for their strength and resilience. Their performance and most common modes of failure are described. Surface and sub-surface indicators of failure are given along with examples of how these could be assessed quantitatively.

- Chapter 6 – looks at the various types of sloped revetment (used to protect bank slopes against erosion) used with linear flood defences and watercourses also briefly describes miscellaneous types of flood defence asset outside the initial scope of this work.

- Chapter 7 – describes a number of case studies and site-based trials carried out during the research. These are included to exemplify and highlight some of the key findings of the work.

- Chapter 8 – gives the main conclusions drawn and summarises the key aspects of the research.

- Chapter 9 – presents potential revisions and additions to asset inspections based on the research. Includes discussion of the practicalities, potential benefits arising and the changes required to embed them within a flood defence asset management system.

This research is highly user focussed and the target audience for this report is flood defence asset managers, consultants within the field and flood risk management researchers with an interest in the management of flood defence infrastructure. The language and terminology used in the report reflects this target audience.
2 General principles and methodologies

2.1 Introduction

This chapter covers key concepts relevant to the project starting with a brief discussion of asset monitoring and its objectives. Various types of asset monitoring relevant to the aims of this work are discussed in some depth.

Details of and the differences between the various spatial levels of monitoring are described including the benefits and limitations arising at each level including discussion of how the various spatial levels of monitoring can be integrated to provide a more effective and efficient level of asset management.

The chapter also discusses briefly the issues in quantitatively assessing assets distinguishing between a full survey of asset parameters and the use of quantitative measures to detect change and potential deterioration.

2.2 Objectives of asset monitoring

In any discussion of the fundamental issues surrounding infrastructure asset monitoring it is important to establish and clarify the main objectives of such processes. Assets can include a wide range of features and vary greatly in size so only general issues will be considered at this stage. For example, the principal objectives of an asset monitoring programme can be classified into four broad areas:

- Ascertain the current condition of the asset.
- Assist in predicting the likely performance of the asset and its contribution to flood risk.
- Assist in ensuring that the infrastructure system as a whole functions as required.
- Assist in reducing or optimising maintenance procedures

These cover the primary motivation for and benefits arising from an asset monitoring programme. Each of these will now be described with specific regard to their relevance in a flood defence asset management context.

2.2.1 Ascertain the current condition of the asset

Assessing current asset condition is the principal aim of an asset monitoring system. This assessment could be in either qualitative or quantitative terms. For example, a condition grade value (1-5, Excellent – Very Poor) or physical property such as crest height and the associated Standard of Protection (SoP) it represents (5.25m, 1 in 100).

Overall asset condition is typically assessed by the consideration and inspection of the various sub-elements of the asset and the relationship between the elements that affect asset performance. In flood defence asset monitoring, this can involve the assessment of each individual cross-sectional element, as with the current inspection regime, or by assessing the asset in terms of all potential failure modes and their associated visual indicators, as with the methodology for performance based visual inspection proposed in the initial phase of the FRMRC (Long et al, 2006).
2.2.2 Assist in predicting the likely performance of the asset compared to its specification.

In addition to assessing current asset condition, a critical use of any asset monitoring system is in assessing future asset performance. This is principally informed by the assessment of current condition, performance models and the application of likely deterioration or damage processes. Performance and deterioration models are approximations of reality based on historical data and scientific models. Predictions of future performance require various assumptions to be made (e.g. asset loading, environmental conditions, third party interference with asset).

2.2.3 Ensure that the infrastructure system as a whole functions as required

Another important motivation is to inform the assessment of the overall flood defence system containing the individual asset being monitored. Once the current asset condition has been assessed and predictions made about likely future performance, these can be combined with results for other assets within the overall flood defence system. Condition and performance of the entire flood defence system can then be estimated. This information for the overall system can then be used to inform decision making by asset managers and highlight critical elements of an overall asset system.

2.2.4 Reduce or optimise maintenance procedures

The results of asset monitoring and predictions for future performance (of both the individual asset and the overall flood defence system) can be ultimately used to produce a better plan for asset maintenance and management. Effective asset monitoring enables earlier intervention when potential faults or defects occur.

Earlier intervention in asset maintenance can lead to significant savings (both in terms of time and cost) and ensure that the protection offered by the asset or flood defence system remains satisfactory throughout its lifespan. This lifespan could also be considerably extended in comparison to a similar asset that is not regularly monitored and maintained (Flikweert et al, 2009).

2.3 Visual inspection

Asset inspection and monitoring is usually carried out using a tiered approach: visual inspection is the bottom tier. It is easy and cheap and therefore practical to do regularly for all assets. The lower tier only provides a broad screening and therefore needs to be supplemented for high risk / complex assets by methods that are better but more expensive and time consuming. The key aim of the lower tier is to provide triggers for the assets that need higher tier inspection. However, visual inspection does require expert knowledge and experience, and can be a subjective judgment. It is sometimes referred to as Non-Destructive Examination (NDE), though not usually within the context of infrastructure asset management.
Visual inspection can, in most cases, only provide information on the condition of the surface of the asset. In some special cases, it can be used to infer something about the sub-surface conditions. A detailed discussion of visual inspection methods used for the management of flood defence assets in the UK can be found in previous work undertaken as part of FRMRC1 (Long et al, 2006).

A typical visual inspection or NDE does not require any quantitative assessment of the asset and instead relies upon a qualitative assessment based on the training, judgment and experience of the inspector. A set of visual features or indicators are assessed visually and results are recorded and combined to produce an overall score for an asset measured on some predefined, abstract scale representing asset condition. Examples of such scales are Condition Grade (Environment Agency), Condition Index (US Army Corps of Engineers) or Soil Slope Hazard Index (Network Rail).

Both the strengths and weaknesses of Visual Inspection or NDE have been well documented (Long et al, 2006) and will not be repeated here. However, those benefits and limitations directly relevant to this work are summarised below:

- Visual Inspection can provide a quick assessment of asset condition without requiring the input (and cost) of a professional consultant or measured survey.
- Assessments produced are subjective judgments of surface condition only. However, visual findings at the surface may be indicative of sub-surface condition.
- Visual Inspection does not generally include the quantitative assessment of features. For example, in flood defence monitoring it is not efficient and accurate enough for assessing asset geometry either for individual assets or entire asset systems.
- Typically, visual inspection only classifies condition into a small set of possibilities. For example, current visual inspection of flood defences in the UK classifies condition into only 5 potential states (condition grades) for an asset.

2.4 Remote measurement

Remote measurement involves the assessment of some properties of an object or entity without the need for close physical contact with that object or entity. In the context of this work it refers to methods and techniques for assessing flood defence assets or the surrounding terrain features from a mobile or fixed platform some distance from the asset. The platform used could range from space based satellites and aircraft to terrestrial vehicles or fixed ground positions. Often the term remote sensing is used when satellite based systems are used.

Remote measurement methods can be broadly categorised into active or passive systems. Active ones transmit some form of energy and then record the reflection or backscattering from the target. Examples of active remote measurement systems relevant to this research include LiDAR, Radar or Ultrasonics. Passive systems detect existing sources of energy present such as light or infrared radiation. Photography or Near Infrared photography would be examples of passive systems with potential for flood defence asset monitoring.

It should be noted that in the context of the tiered approach mentioned earlier, remote measurement could be in the lower tier and possibly even lower than ‘visual
inspection’ where it can be done cheaply for a large area. For example, in the future it may be possible to use LiDAR on low-consequence systems to ascertain that the defence is there and only do visual inspection where LiDAR is inconclusive.

2.4.1 Light Detecting And Ranging (LiDAR)

LiDAR is a proven technology for rapid and accurate assessment of the terrain and large natural and man-made structures. Its use in the production of Digital Surface Models (DSMs) for flood mapping and inundation modelling is now commonplace. It is also used to survey man-made and natural features for a variety of applications (e.g. slope monitoring in mining and quarrying, structural health monitoring and even meteorological surveying of the atmosphere, as exemplified by its use in monitoring atmospheric ash levels arising from recent volcanic eruptions in Iceland.

The process of acquiring, processing and analysing LiDAR data is detailed in previous FRMRC work (Smith et al, 2006) in more depth than required in this context but a brief summary of the steps involved for an aerial LiDAR survey is given below:

1. The flight path and altitude of the aircraft are planned based on the area to be surveyed and the detail and accuracy of the survey stated in the specification.
2. The survey flight is carried out, which will be dependent on weather conditions.
3. The measurements are recorded and processed to produce a ‘cloud’ of coordinated points (E, N, H) that are quality controlled.
4. Normally from the ‘point cloud’ a regular grid Digital Surface Model (DSM) is created at an appropriate interval. A Digital Terrain Models (DTM) can be further generated by the remove of above ground surface features to produce a ‘bare earth’ model. The ‘above ground level’ surface features are also available for further use and analysis.

Figure 2.1 shows the typical elements of an aerial LiDAR survey of terrain such as that used in topographical mapping applications.

![Diagram of typical aerial LiDAR survey](taken from Smith et al, 2006)
Static ground based LiDAR surveys, normally called Terrestrial Laser Scanning (TLS), can produce more accurate results than an aerial or terrestrial vehicle survey but obviously require a great deal of time to survey large areas. They are commonly used to accurately monitor small scale, safety-critical structures such as quarry slopes or dams and could be used for continuous monitoring applications (see section 2.5).

Terrestrial vehicle mounted LiDAR surveys, normally called Mobile Laser Scanning (MLS) and LiDAR (normally used to refer to airborne laser scanning) offer the greatest potential in asset monitoring applications due to their combination of accuracy and coverage. Since the distance from scanner to target is often a key factor in the precision of LiDAR (Anderson et al, 2005), the type of platform chosen and its survey path will determine the trade-off between accuracy and coverage in the results obtained.

Specific details on the use of LiDAR for asset monitoring purposes including discussion of the effects of platform, scanner and target condition can be found in the relevant chapters on flood defence asset types and in particular, chapter 3, which discusses the monitoring and assessment of earth embankments.

It is also possible with modern LiDAR technology to use it under certain circumstances for bathymetric surveying. This has great potential application in the context of flood defence monitoring.

2.4.2 Photogrammetry

Photogrammetry, or more accurately stereo photogrammetry in this context, is the practice of determining the geometric properties of an object from a photograph. In terms of infrastructure asset monitoring, the principal form of photogrammetry used is via aerial images taken from an aircraft. However, terrestrially taken photographs from a fixed reference point or ground vehicle would be capable of producing quantitative assessments of asset geometry and will be further examined in the relevant sections on specific asset types.

Detailed analysis of photogrammetry and its capabilities can be found in the work underpinning this research arising from the initial phase of the FRMRC (Smith et al, 2006) but some key points regarding the use of aerial photogrammetry of relevance to this work are:

- Camera, GPS and Inertial Measurement Unit (IMU) are often used today to produce ortho-rectified imagery (imagery with the same geometric characteristics as a map) of terrain.
- Wider coverage per swathe than LiDAR can be achieved due to the camera geometry of photogrammetric survey
- High resolution photography from fixed wing aircraft can produce quantitative assessment of terrain and assets to a similar level of accuracy as LiDAR
- With manual correction photogrammetry can pick up features not detectable by LiDAR
- Photogrammetry requires a clear view of the target surface. The capture of ‘normal’ photographs on film and digital imagery can be limited by atmospheric conditions such as low cloud, fog or heavy rain and general light levels.
Performance based inspection of flood defence infrastructure: Integrating visual inspection and quantitative survey measurements  
FRMRC Research Report SWP4.2

- Photogrammetry cannot penetrate vegetation. Ground conditions could be obscured from assessment when vegetation cover is extensive.
- Photogrammetry requires more intensive post-processing than LiDAR
- Photogrammetry is capable of producing high quality colour images with a resolution of typically 5cm/pixel offering the potential to detect relatively small scale surface deformations or changes.

**Near infraRed (IR) photogrammetry**

Near IR Photogrammetry works in an identical way to standard photogrammetry except that the sensor or film used in the camera is more sensitive to the infrared section of the electromagnetic spectrum. The near refers to the fact that the sensor or film only works passively and cannot detect far into the infrared band of the spectrum such as is the case with thermal imaging/thermography.

In the context of this project, Near IR Photogrammetry has a singular property that makes it potentially useful; vegetation and water is highlighted due to its reflectance to the near IR band of the spectrum. Near IR Photogrammetry has been used to monitor crop growth and type. In terms of flood defence asset monitoring, the highlighting of vegetation means that bare sections of earth stand out. This could be useful when assessing grass cover on earth embankments and will be further discussed in section 3.3.6. It can also highlight differences in vegetation type and structure which could be indicative of the phreatic surface or even potential failure, e.g. presence of water loving plants where seepage is occurring.

**Multi/Hyperspectral imaging systems**

This category includes imaging systems that capture image data at a range of wavelengths in the electromagnetic spectrum. It can include wavelengths that lie outside the visual spectrum, including Near IR and deeper into the Infrared. The difference between multi and hyper spectral imaging is that hyperspectral imaging is more discriminatory in the individual bands of the spectrum it can analyse.

These types of imaging system are typically deployed from space satellites and aircraft. The CASI imaging system is an example of this type of remote measurement equipment and is already used by the Geomatics Group for the Environment Agency in the UK.

Similarly to Near IR Photogrammetry, multi and hyperspectral imaging systems are commonly employed in the monitoring of agricultural vegetation and would be of potential use in assessing the presence of vegetation on flood defences. Their increased ability to monitor specific bands of the spectrum raises the potential of identifying specific vegetation types over Near IR alone. Potentially this could be used as a proxy for sub-surface conditions such as the presence of saturated ground or specific soil types. Again, this is most relevant to earth embankments and will be discussed in more detail in the relevant chapter.

**2.4.3 Radar based sensing (SAR, InSAR, ASAR)**

Radar is another active remote measurement system. There are a number of potential methods and techniques for remote measurement via radar including Synthetic
Aperture Radar (SAR) and its variants (e.g. ASAR and InSAR). Specific details regarding the nature and operation of these technologies will not be described here but can be found in a number of sources including previous work by one of the authors (Smith et al, 2006). InSAR is the method most suited to asset monitoring applications due to its aptitude and accuracy in the detection of change or movement to a target over time.

InSAR is a radar based technology that can be used to survey the earth surface and generate topographical information. Its potential use in flood plain mapping was examined in previous work under FRMRC1 (Smith et al, 2006). It can be used to produce a digital elevation model and like the other system level technologies could utilise a variety of space-based, airborne or terrestrial platforms.

**Figure 2.2 : InSAR image of the Thames in London (source IESSG, The University of Nottingham)**

A key feature of InSAR is that it is not affected by cloud cover or darkness. The standard shorter wavelength systems (C-band and X-band) cannot penetrate vegetation and will therefore produce elevation on the top of any vegetative cover. Longer wavelength (P-band and L-band) can penetrate vegetative cover to give a bare-earth elevation of the ground features. It may therefore be of greater use in surveying flood defence assets. However, the effect of Faraday Rotation (Meyer and Nicoll, 2007) needs to be mitigated in using the longer P-band and L-band InSAR from space and a lack of suitable frequencies due to mobile phone networks may affect its use from an airborne platform. These issues are however both resolvable. Ground based InSAR would not be subject to these issues but would be subject to other problems common to terrestrial based systems mentioned previously and has not been established as a viable method for use in the context of this work.

### 2.4.4 Sonar and wide swathe bathymetry

This section is specifically concerned with methods employed from a water-based vehicle. Sonar and ultrasound scanners used to measure underwater topography are examples of these methods. Water based surveying can be useful at both the system and the asset level. At the system level, boat-based monitoring equipment can be used to produce a view of assets over a sub-reach or reach. Side-Scan Sonar is the
technology most likely to be of use in enhancing the visual inspection of assets since it enables measurement to the asset below water level, e.g. toe of the structure.

Figure 2.3. Wide swathe bathymetry of Blythe harbour, Northumberland (source: GeoAcoustics)

Sonar is used currently at the EA, albeit typically within a fisheries management context and the channel profiles generated by this could prove useful in asset management. Tidal regions seem to be most commonly associated with the use of sonar based surveying of fluvial and estuarial channels. The erosive effect of regular incoming and outgoing tides makes toe scour (see section 4.1.1) a major concern. It is likely to be of most use where the visibility of the toe of an asset is not possible through a standard visual inspection due to access or hydraulic conditions.

2.5 Fixed point continuous monitoring

Monitoring of assets through the installation of electronic and mechanical sensing equipment is often employed in the assessment of dams and reservoirs due to the strict regulatory requirements related to their management. The two main advantages provided are that the assets can be continuously monitored and the reduced requirement for manual inspections by inspector or vehicle.

Continuous monitoring will produce a more accurate assessment of change over time than inspection records gathered on an irregular (e.g. 6/12/24 monthly) basis. It can also record asset parameters at times of both high and low loading conditions which can be highly significant data in modelling asset performance. Continuous data on asset condition could also be used to trigger a local, more detailed, inspection if results from monitoring indicate that a potential problem has occurred with the asset. The main issue in utilising fixed point monitoring systems for flood defence structures is the intrusive nature of their installation.

Meijer and Koelewijn (2008) describe on-going work at the Ijkdijk facility in the Netherlands examining the viability future potential of sensor networks integrated with earth embankments for early detection of geotechnical problems and hydraulic loading conditions.

2.5.1 Motion and positional sensors

This category includes a wide range of devices capable of detecting movement of an infrastructure asset. This can be achieved by detecting the relative motion of the sensor or by assessing changes to their absolute position. Their scale, accuracy and mode of operation vary widely and they range from the relatively inexpensive to
extremely costly. Examples of the types of sensor applicable in this context from the most simple to the more complex are given below:

- **Gauges and Tell-Tales** – These are the simplest types of motion detector and consist of engineering tools which are placed on an asset to monitor changes such as the expansion of cracks or deterioration of material. This type of technology has been used in structural health monitoring for a considerable time. Figure 2.4 gives a very simple example of a tell-tale that can measure crack width on a structure.

![Figure 2.4: A simple tell-tale for measuring crack width on a structure. (Mastrad.com)](image)

- **Accelerometers** – These are devices which detect relative motion through the measurement of acceleration of the sensor. They can be used to detect subsurface changes to an asset and range greatly in the accuracy and degree of motion they can detect. These devices are now widely in use in electronic devices such as video game controllers or mobile phones. This has led to a reduction in their dimensions and cost. Robust accelerometers suited to installation on site are widely used in infrastructure monitoring for bridges or dams. An example relevant to this work is given in section 4.2.2.

- **Inclinometers** – These are devices to measure the angle or tilt with respect to gravity. Often these sensors employ an accelerometer and/or gyroscope as the mechanism for detecting tilt. They can be used to detect changes to slope angle such as those caused by landslide or subsurface movement. In addition to being used as sensors, inclinometers can be used as a measuring device and could be utilised as part of a detailed inspection to quantitatively assess slope angles.

- **Time Domain Reflectometry (TDR)** - A TDR is an electronic device that can be used to measure movement, typically in an earth or rock slope. It is a slightly invasive technique as a conductive cable must be embedded into the embankment. The method detects movements in a slope as they cause a bend or break in the cable. Early implementations of the method required staff to monitor the equipment manually and could not detect small movements in a slope. Recent developments (Farrington and Sargant, 2004) have advanced the technology so that it could be used for remote monitoring of slopes and improved its accuracy significantly. It has been employed in the mining industry and for the monitoring of dams.

- **Radio Frequency IDentification Tag (RFID) Network (Wireless/Mesh Technology)** – By integrating RF sensors with wireless technology it is possible to produce a network of sensors that can report their positions relative to each other. Such a network can therefore be used to detect any change or movement within a structure. This is still an emerging technology and requires further
investigation to gauge its future potential for flood defence asset monitoring. The RFID sensors would, in general, need to be dispersed throughout the asset and would therefore be best suited to inclusion during the construction phase of new assets. Employing this technology in an existing asset would be highly invasive and outside the scope of this work.

- GPS Station network – A series of fixed GPS stations can be used to detect movement to a very high degree of accuracy. This type of sensor network would be most suited to monitoring over a large area. An example of this already exists at the national level: the BigF project (Bingley, 2006). This has been used to detect small changes in land elevation in the UK. Further details on this and its applicability to flood defence monitoring are given in section 2.8.1.

2.5.2 Fixed cameras

A standard video or still camera that takes regular images of an asset or group of assets from a fixed location is another method that is increasing in popularity. It reduces the need for inspection staff to visit a site until there is a definite need for intervention. The degree of assessment provided by a fixed camera will be determined by the quality of the camera sensor and the fixed point chosen. A fixed camera could be capable of some rotation and optical zoom to increase its utility though both these options would significantly increase power consumption which could be an issue if employing battery power.

Since the camera position is fixed and known, photogrammetric techniques could be employed to enable quantitative assessment of the images obtained through single or multi-camera methods.

The use of fixed cameras for monitoring is already being employed by the EA in a set of trials focussed on trash screens at culverts and is further detailed in appendix D.

2.5.3 Moisture detector

The presence and degree of saturation in a soil is an important factor in many of the performance models relating to flood defence infrastructure assets such as embankments and walls. Unexplained or unexpected changes to moisture levels can be important indicators of a number of potential failure mechanisms (e.g. piping and backfill washout). Long periods of changing moisture levels within an embankment have been shown to be an initiator of fine fissuring (WP4.1 FRMRC1).

A range of potential methods and technologies including piezometers and resistivity equipment can be used to measure the moisture content within a soil. Piezometers actually measure pore water pressures from which it is possible to infer the moisture content. They can utilise a variety of measuring mechanisms with differing sizes, accuracies and associated costs. They are widely used in geophysical monitoring projects. Ground Penetrating Radar (GPR) is another tool which can be used to detect sub-surface moisture content but it is not typically employed as a fixed point sensor.
2.5.4 **Micro-Electro-Mechanical Systems (MEMS)**

A MEMS is not an actual sensing type in itself, it is rather an integration of mechanical elements such as actuators, accelerometers or piezometers with electronic components on a common silicon substrate. Typically MEMS combine sensing technologies such as motion, moisture and temperature detection capabilities.

As inferred by the Micro- appellation, these devices can be very small and can be installed with minimal intrusion to the asset. Multiple MEMS sensors can be installed in a single borehole and can be combined with wireless technology to enable remote logging of their output to a monitoring centre. These properties make them of particular interest in the terms of this work.

MEMS are already widely used in Dam and Reservoir monitoring and advances in this technology are leading to reductions in unit cost which will make them more attractive in terms of flood defence monitoring in the future.

Since they are integrated and miniaturised versions of existing sensors they would be applicable in similar applications to those described under the individual sensors in the previous sections and under the relevant sections of the asset specific chapters (chapters 3-7)

Rowsell (Rowsell and Owen, 2009) describes the potential for the use of MEMS in the monitoring of rail infrastructure networks which share many properties with flood defence infrastructure. This report also contrasts their use with many of the competing technologies for quantitative assessment of infrastructure assets, e.g. remote measurement methods or time domain reflectometry.

2.5.5 **Integrated sensor arrays**

Ideally a monitoring system could be set up which combined into an array a number of the previously discussed methods of monitoring. This sensor array would then be capable of transmitting a range of asset parameter data and providing a record of asset deterioration or damage over time. Additional monitoring devices to record details of asset loading or weather conditions could also be included to provide a holistic view of site conditions and be used in performance modelling of the asset to determine its fragility curve. Sensor arrays are currently used in some dams and reservoirs to enable real time monitoring of condition. A potential mechanism for their employment in flood defence monitoring is explored in section 9.3.

Wireless networks can be utilised to transmit telemetry from the various sensors and there is a large body of ongoing research into their potential use in structural health monitoring systems (Thomson, 2006).

2.6 **Detailed survey**

This category refers to asset inspections that would typically be carried out by trained professionals or experts rather than standard inspection operatives. Detailed investigations are generally the most time consuming and expensive inspection type
but offer the highest degree of fidelity in terms of their assessment of asset condition and likely performance.

2.6.1  **Detailed topographic survey**

Topographical surveys are routinely employed to gain an accurate and detailed assessment of the surface geometry of an infrastructure asset and the surrounding terrain. Topographical data can be acquired via remote measurement methods as described in section 2.3.2. However, a topographical survey in this context refers to a highly accurate and detailed survey carried out by a qualified surveying consultant.

Typically, a detailed topographical survey would be carried out at the ground level using surveying equipment and methods e.g. theodolites, levels, EDM, or more recent developments such as, robotic total stations or kinematic GPS (though it could also employ remotely sensed survey data such as LiDAR and aerial photogrammetry).

2.6.2  **Non Destructive Testing (NDT) methods**

Numerous types of NDT methods exist and functionally speaking the term would include all the types of inspection described thus far. In terms of the types of detailed investigations described in this section, NDT refers to the range of non-invasive tools and techniques that could be employed to assess the condition of an asset not covered under sections 2.3.1-2.3.3. NDT methods are often material specific.

Examples of this group would be the use of specialist engineering instruments like Schmidt hammers for testing the strength of concrete structures or ultrasonic scanning for testing the thickness of steel sheet pile. In practical use, this latter method would often need to be performed from a water-based vehicle to gain access to the sheet pile under investigation. No current use of this technology by the EA has been identified and it is likely to be a method employed by consultants on an ad-hoc basis. Because of this it is unlikely to form an integral component of general system level asset surveys. Advances in technology and reductions in cost may however lead to this type of scanner becoming more commonly available and its potential should be examined to some degree.

A comprehensive list of NDT methods applied to flood and coastal defences was produced as part of the EA/Defra RandD programme by Posford Haskoning (Ogunyoye et al, 2004). This describes each method and how it could be applied. Many of the methods are material specific and require expertise and extensive training to carry out. The results arising from these methods and tools are often difficult to interpret without knowledge, training and experience. These are therefore likely to fall outside the remit of this project and stay within the purview of an engineering consultant’s survey or inspection.

2.6.3  **Invasive testing and geotechnical surveys**

Invasive or destructive testing encompasses a variety of potential methods that require some removal of asset material or constituents in order to predict the condition of the overall asset. Depending on the nature of the infrastructure asset, invasive testing
could also refer to geotechnical testing of the earth supporting and surrounding the asset. This is particularly true in the case for flood defence assets where much of the asset’s strength is reliant on their underlying foundations. As stated in section 1.3, this type of monitoring is outside the scope of the project and will not be discussed further. However, some invasive element is typically required for the installation of many of the sensors described in section 2.5 and exception is made in these instances as it provides additional benefit in the form of continuous monitoring capabilities.

Some forms of geotechnical survey are not invasive and are therefore of potential interest. Examples of these would include GPR and resistivity assessment. These are given in more detail under the section on sub-surface monitoring of earth embankments (section 3.4).

2.7 Detailed inspection

The concept of a detailed inspection of an asset would be aimed at the level between a standard visual inspection and the detailed survey described in the previous section. It would combine elements of each and would likely include quantitative assessment whilst remaining within the capability of a trained operative rather than requiring an expert consultant.

A detailed inspection would intend to provide a more accurate and comprehensive assessment compared to a visual inspection. Ideally it should go beyond the scope of visual inspection and assess more than just current condition. For example, a detailed inspection could assess the potential lifespan of the asset and calculate the particular mode(s) of failure most likely to occur given current condition. It may also provide an objective, risk based assessment of performance and likely failure.

A detailed inspection would not be carried out as a matter of routine but would be activated under a range of potential conditions. Examples of these include where:

- A visual inspection has identified a potential concern with asset condition but has not been able to clarify the nature of the fault.
- An asset is critical to the performance of the entire infrastructure system and the consequences of failure are high.
- Previous problems with asset performance have existed and the need for more detailed monitoring has been determined.

The extra detail produced at this level would require additional time and/or resources. However, this is balanced by a reduction in the need for detailed investigations by external consultants and earlier identification of, and intervention in, potential faults with an asset. Detailed inspections would need to be asset specific and are therefore discussed further in the relevant sections in chapters 3-7.

In terms of flood defence monitoring in the UK, a number of studies have proposed the introduction of a detailed inspection step within the overall infrastructure management programme and a desk study was recently completed by Royal Haskoning into this specific topic. Their work provided a potential framework for detailed asset inspections and outlined key aspects of the process and how it would operate in practice. If detailed inspections were to be introduced for flood defence
management by the EA then Haskoning’s framework seems a logical starting point for its development.

2.8 Spatial scales of monitoring and inspection

Monitoring and inspection of assets can be carried out at a range of spatial scales depending upon the specific methodology or technique being employed. For example the remote measurement methods described in section 2.4 generally provide optimal use when employed to cover a group of assets in a single survey. The platform employed determines the specific scale (e.g. space based platforms cover a very wide area and terrestrial based remote measurement typically focuses on a small group of assets). In contrast, the detailed investigations and inspections are typically focussed on a single asset or small group of assets.

For the purpose of this work three spatial scales have been identified as being most relevant; system/catchment, reach/sub-reach and asset. Each of these levels of monitoring is described in the following sections.

It should be noted that although a monitoring method might be employed at a higher scale it can still provide detailed information that is applicable at the asset level. Correspondingly, lower scale inspections can also be integrated to produce an assessment of the overall asset system.

2.8.1 Catchment or regional level

Catchments refer to the highest scale relevant to this project. These could cover an entire group of fluvial reaches and be as large as an entire region (as defined by the Environment Agency in England and Wales. Examples of catchments for the UK can be found on the Environment Agency’s website. The three catchments defined for the entire Midlands region are shown in Figure 2.5.

Figure 2.5: Environment Agency’s catchments for the Midlands region in the UK [taken from EA website – Midlands region Catchment Flood Management Plans (CFMP): accessed on 20/02/2010]
A descriptive example for one of the catchments shown is given below:

*The River Severn CFMP covers the catchment down to Gloucester, including tributaries, e.g. the Avon and Teme. The CFMP includes much of the counties of Shropshire, Worcestershire, Warwickshire and Gloucestershire, covering 15,000 km² and a population of over 2.24 million people.*

[Taken from EA website – Midlands region Catchment Flood Management Plans (CFMP): accessed on 20/02/2010]

The potential detail provided by catchment level monitoring enables the observation of large-scale effects such as mining subsidence that might not be evident at lower spatial levels of monitoring. Catchment level monitoring can also enable the quantification of the topography, land use, size and other features of a catchment. Changes to these properties occurring over time may also be detectable and would be potentially useful in flood risk management (as part of CFMPs).

Monitoring options at the catchment level are more limited as there are few methods that provide such broad coverage. Principally, these include space-borne platforms (or high altitude airborne platforms) and large, geographically dispersed, fixed sensor networks. Catchment level monitoring methods are likely to be less suited for providing accurate assessment of individual assets within the catchment than the more detailed levels described in sections 2.4.2 and 2.4.3.

Above the catchment there is also regional, national or international levels of potential monitoring. Regional or national level land movements are a potentially useful input in long term management and planning of flood risk but are not directly relevant to this work.

Examples of potential methods at the catchment level are described in the following sections.

*Satellite based systems*

Numerous examples of space based monitoring systems exist including traditional visual spectrum photography and radar-based systems described in Section 2.4.3. Photographic images taken from space have been used to model terrain and to identify changes through subsidence or natural events such as landslides or flooding. Their potential use for studying floodplains was examined in some depth under FRMRC1 WP5.2 (Smith et al, 2006). Results from this and other work that are relevant to the use of satellite-bases systems for the work of this project will be briefly summarised here. An example of satellite photography is shown in Figure 2.6.

Space based photography can be acquired from geostationary and polar orbiting satellites. Geostationary satellites can provide constant monitoring of a single area of the earth whereas polar orbiting systems will perhaps only scan an area twice per day. Polar orbiting satellites, however, possess the ability to produce more detailed imagery due to their much lower orbit (approximately 600 miles compared to 22000 miles).
Of the system level methods space-based systems, in general, provide the lowest cost per square kilometre surveyed due to their immense coverage. They are, however, limited in terms of image resolution. The highest resolution of image that can be currently acquired from satellite is approximately 0.5m per pixel. It is unlikely that most asset level changes would be easily identifiable from even the highest resolution image from a low orbit satellite.

Satellite photography, at least in the visual spectrum, has another major limitation in that it is affected by cloud cover. This will be a particular issue in areas with high levels of cloud cover such as the UK. An important advantage of these systems is that the satellites are orbiting and monitoring continually and there is no need to initiate a survey exclusively for the purposes of flood defence monitoring. Conversely, the imagery can only be captured at the time when the satellite is in position over the target area and it is consequently not so useful for rapid response surveys.

**GPS station networks**

Networks of fixed GPS stations such as those networks used to monitor land movements and sea level changes in the UK (Bingley, 2006) can be employed to monitor large-scale changes to asset systems. It is however unlikely that these would be of great use in monitoring specific movements in specific flood defence assets (unless a GPS receiver was placed on the asset itself) but data from these networks could be useful in highlighting areas of increasing risk from flooding due to overall land movements. This could be used to trigger a more detailed topographical survey of, for example, defence crest profiles in a region.

Bingley et al (Bingley et al, 2008) provides an example of the potential role of fixed GPS networks in flood risk management and planning focussing on the Thames Estuary region of the UK. They describe how the findings from long term GPS station single point readings can be correlated with satellite based InSAR DSM data to produce accurate assessments of land and sea level changes over time and make more accurate predictions regarding future flood risks.

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**Figure 2.6: Satellite photo of London showing the Thames and Greenwich (taken from Image Science and Analysis Laboratory, NASA Johnson Space Center)**
Aerial surveying

Airborne surveys at mid- to high-altitude using fixed wing aircraft offer a flexible and relatively high detail means of monitoring asset systems at the catchment level. These could incorporate a range of scanning methods such as LiDAR, InSAR, or Photogrammetry (visible spectrum/Near IR/Hyper or Multi-Spectra).

2.8.2 Reach/sub-reach level

There are a variety of definitions of a reach. In flood risk management terms, it can be considered as a section of river that could encompass a bend and often in technical terms covers a length in which the flow does not increase significantly – which is generally between points of confluence with other streams. Reaches can then be broken into sub-reaches for more detailed analysis, identification or management purposes. The exact size of a reach or sub-reach is not clearly specified and is dependent on the specific location and requirements of local flood risk management. In highly populated, urban areas reaches may cover a much smaller area than in rural areas where the impact of flooding and therefore its management is of less critical concern.

For the purpose of this work, the reach or sub-reach scale of monitoring represents a small to medium sized group of flood defence assets within a relatively small geographical area.

At the reach or sub-reach level, a range of methods can be employed to monitor a group of assets. Typically these would be performed from a mobile platform such as an aircraft or terrestrial vehicle. Monitoring methods from the catchment level described in 2.8.1 would also be applicable, though the resolution and precision of such data might not be at a sufficiently detailed level for the needs of managing the reach or sub-reach.

At the larger end of the scale (large reaches), aerial surveying of assets by fixed wing aircraft would be a suitable means of monitoring. For small sub-reaches, ground-based vehicles such as the Lynx Mobile Mapper shown in Figure 2.7 might be suitable (assuming vehicular access to assets is possible). Unmanned Aerial Vehicles (UAVs) also offer a potential source for rapid and efficient monitoring of small sub-reaches. At present, the reliability of this type of survey is of concern.

Where terrestrial vehicle access to assets is limited or obstructed, another option available specifically in this context is the use of waterborne vehicles. Boats can be used as the platform for a range of monitoring methods e.g. photography, LiDAR or video. In addition, surveying using sonar can be employed to assess the condition of an asset below the waterline.
A commonly used method for monitoring infrastructure assets rapidly and accurately at the reach level is the use of high resolution LiDAR integrated with digital photography and full motion video from a helicopter based platform flying at low levels. This type of monitoring setup is often referred to as the FLI-MAP system in reference to a proprietary version operated by Fugro amongst others. This type of system is particularly suited to asset monitoring applications where there is a need to survey, at a high resolution, relatively narrow but extensive areas such as transport corridors or fluvial channels. There are a number of recent studies describing the use of this type of system in flood defence monitoring (Burgess, 2004; Ogunyoye et al, 2004; Smith et al, 2006; Scott et al, 2005).

2.8.3 Asset level

This is the lowest level of monitoring described in this report. It includes those methods and techniques that operate at a fixed location or on a single asset at a specific time. Traditional methods of visual inspection are carried out at this level and most ground based methods (except those employing motorised vehicles) would be at the asset level.

Examples of asset level monitoring methods relevant to this work would include the following:

- Quantitative assessment of asset performance features. For example measurement of the width and length of any cracks or other defects.
- Surveying of asset geometry and any surface deformations using standard surveying tools and methods. These include theodolites, levels, robotic total stations and Real Time Kinematic GPS (RTK GPS).
- Photography of key asset features which should preferably be geo-referenced to enable accurate quantification of those features.
- Ground Penetrating Radar (GPR) which offers a method for sub-surface monitoring at the asset level (or sub-reach level if attached to some form of mobile platform) and can detect voids or other sub-surface anomalies.
Various NDT tools and techniques which can be used to monitor the condition of specific materials that form part of a defence asset. See section 2.3.4 for further details and examples.

Further details of these, and other, asset level methods are provided in the relevant chapters for each principal type of linear defence asset (chapters 3-7).

2.9 Quantitative assessment of infrastructure assets

This section provides a brief discussion of some general issues specifically related to quantitative assessment. Firstly, the differences between, and potential implications of, absolute and relative assessment are described in the context of infrastructure asset monitoring. This is followed by a discussion of accuracy and precision of monitoring methods and how this impacts upon asset monitoring and management.

2.9.1 Absolute versus relative assessment

The assessment of infrastructure asset properties such as geometry, material condition and any associated defects can be done on an absolute or relative basis. Absolute assessment, such as traditional surveying, requires the acquisition of the actual value of the properties being assessed such as crest height or crack width. Relative assessment, such as change detection, provides an assessment of some asset property relative to another property or in comparison with a previous value for that property.

Absolute values are defined in terms of a datum. For example, in the UK absolute crest height would normally be measured as height above Ordnance Datum in metres.

Relative values would measure changes in quantities/features. This is often a previous, historical, value recorded for the same feature enabling the degree of change to be assessed without absolute assessment of the feature itself. In some monitoring applications the degree of change for a given asset feature is all that is necessary. An example of a monitoring method that can only assess relatively (without additional data) is InSAR. InSAR data cannot provide an assessment of elevation on its own but comparison between two InSAR datasets can detect any change to a very high level of precision and accuracy.

Absolute assessment is often preferred to relative assessment. However for some monitoring applications a relative assessment of change is sufficient. Other factors such as cost, accuracy or ease of use may also make a relative assessment more appropriate for a specific monitoring application.

2.9.2 Accuracy and precision of assessment

In colloquial terms, accuracy and precision are often used interchangeably and there is a close relationship between the two concepts. However, it is important to briefly distinguish between accuracy and precision in terms of quantitative assessment as it informs much of the detailed asset specific discussion in chapters 3-7. It is also important to highlight in general terms the degree to which accuracy and precision are required for the various types and spatial levels of infrastructure asset monitoring.
Accuracy can be defined as the closeness of a measured quantity to the actual true value of that quantity. As stated in section 2.2.1, one of the main objectives of asset monitoring is to assess the current condition of the asset and its likely performance. The accuracy of this assessment is obviously of critical importance. An inaccurate assessment of asset condition makes it much more difficult to manage that asset efficiently and ensure its continued performance to specification. Low accuracy typically makes absolute assessment methods of limited use.

Precision is a measure of the variation in results obtained when repeating or reproducing a quantitative assessment. The greater the range or spread of results from an assessment, the lower the precision of that result. In the context of infrastructure asset monitoring, it is important to be as precise as is possible and where imprecision does exists, it should be defined explicitly. High levels of imprecision are a particular concern when employing relative assessment since the comparison between two measurements may not reflect the change to the value of the assessed feature but instead may reflect the imprecision of the assessment method. Conversely, a value may be very precise but not very accurate.

Statistical Noise is another term sometimes used to define the imprecision of a measurement. More specifically, it typically refers to a variation in results that is unexpected or unexplained. A relevant example of noise would be the effect of vegetative cover on the results obtained from remote measurement methods such as LiDAR or Photogrammetry. In both instances the measured surface elevation obtained will vary according to the state of the vegetation and the degree to which it obscures the terrain surface.
3 Earth embankments

3.1 Introduction

Earth embankments are a major element of the report due to their importance and prevalence as flood defences in the UK (and beyond). It also forms the start of the main body of the report (chapters 3-7) looking at some of the major types of linear flood defence asset commonly used in the UK. The chapter will also introduce or expand upon a range of methods and technologies that will then be referred back to in the later asset specific chapters (e.g. LiDAR, GPR, RTK GPS, Aerial or fixed point photography). This accounts for the longer length of this chapter in relation to those following but is not intended to imply that embankments were the sole focus of this work.

A detailed explanation of the structure, construction and performance of earth embankments falls outside the remit of this project though some basic concepts are presented here for the purposes of clarity and to inform the discussion on monitoring and quantitative assessment of embankments. There are a number of other studies that offer greater detail in relation to the structure, design and performance of embankments (Morris et al, 2007; Allsop et al, 2007; CIRIA, 2001)

This report is intended to take an application based approach to the problem rather than a technically focussed approach. To this end, the format of the chapter starts with a brief description of the asset in terms of structure, performance and failure (referring to relevant previous work where possible to reduce length and repetition with work of others). This is followed by a discussion of surface and sub-surface monitoring options. For each asset type, potential indicators of failure and deterioration are described along with discussion of how these indicators could be quantified and monitored and how they relate to asset condition and performance.

The remainder of the chapter then covers the various types and spatial scales of monitoring outlined in chapter 2. It describes how the various methods and techniques available could be employed in the monitoring of flood defence embankments. This is supported by a number of examples of case studies and experimental work described in chapter 8.

3.2 Embankment performance and failure

3.2.1 Structure and performance of earth embankments for flood defence

Earth embankments employed as flood defence assets consist of two raised slopes and a crest, though in some instances additional flat sections (berms) below the crest may be present. Figure 3.1 shows an embankment cross-section illustrating typical features of this type of linear defence asset.
Surface protection, as shown in the diagram, is not considered in this chapter as it is discussed as a separate asset type (revetment/slope protection against erosion) in chapter 5.

Using the source/pathway-barrier/receptor model of flood risk management, embankments form the barrier preventing the water reaching the receptor (people, property, etc.). An embankment’s crest height can be associated with a Standard of Protection (SoP) and any additional crest height exceeding this level is referred to as the freeboard. Water levels exceeding the SoP crest level plus freeboard will overtop (coastal) or overflow (fluvial) the defence leading to water reaching the receptor. This is not technically classed as a failure since the water levels exceed the SoP offered (though this technicality is often not appreciated by those affected by flooding caused by overtopping or overflow).

### 3.2.2 Failure modes, deterioration processes and their visual indicators

There is a large body of literature discussing the modes and methods of failure for earth embankments, many of which have already being referred to (Allsop et al, 2007; Morris et al, 2007; CIRIA, 2001; Bromhead, 2000). In the context of this work, the principal modes of failure used in UK flood defence asset management (RASP/HLM+, etc) and utilised in previous work on performance based visual inspection (Long et al, 2006) are the most relevant and are briefly outlined in Table 1.

Deterioration is the gradual reduction of asset strength due to any cause. This means that a lower loading may be needed to trigger a specific failure mode – there is a change in the fragility curve. It may sometimes be specific to a particular failure mode and the method by which that mode was initiated. In some instances deterioration will progress rapidly with little visual warning (e.g. piping). In other situations deterioration will be a slow process and there will be ample signs visible to an observer (e.g. slope instability caused by long term settlement of the embankment). A particular failure mode may deteriorate at differing rates depending on its cause. For example, overflow leading to erosion could be triggered by long term rutting of the crest caused by foot traffic (human or livestock) eroding the freeboard. Alternatively, an intense storm could trigger the same failure mode rapidly, and with
little visual warning, if the embankment is overflowed for a considerable period. In fact, storm duration is a significant factor in the performance model for this failure mode.

Table 1. Illustration of details of typical failure modes for an earth embankment

<table>
<thead>
<tr>
<th>Failure Mode</th>
<th>Description</th>
<th>Performance Parameters</th>
<th>Visual Indicators</th>
</tr>
</thead>
<tbody>
<tr>
<td>*Non-structural failure (overtopping)</td>
<td>Flooding occurs without breach of the defence due to water level exceeding the crest height</td>
<td>Water Level, Crest Height</td>
<td>None</td>
</tr>
<tr>
<td>Overflowing / Overtopping leading to erosion of outer slope</td>
<td>Water running down outer slope leads to degradation of surface protection and eventual erosion of outer slope over time. Eventually leads to a breach of defence.</td>
<td>Crest Height, Grass quality slop angle</td>
<td>Rutting of crest, Crest Height below SoP, Vegetation on outer slope</td>
</tr>
<tr>
<td>Slope Instability</td>
<td>Geotechnical weaknesses initiate slipping or sliding of either slope. Range of potential causes such as poor design, third party damage, etc. Subcategories include circular slipping, sliding, deep seated failure, etc.</td>
<td>Crack Width, Slip distance, Slope angle, Slip width, Slip height, Slip circle radius</td>
<td>Cracking, slumping or uplift evident, Slope Movement, Animal burrowing, 3rd party damage to slope or toe</td>
</tr>
<tr>
<td>Piping</td>
<td>A pathway for water to pass through or under the embankment forms (due to poor soil condition and/or vermin infestation for example). Water seeps into the asset washing out fill material. Eventual creation of a piping channel from inner to outer side of embankment and can cause explosive blowout and breach</td>
<td>Embankment width, Soil coefficients, Seepage Length, Water level difference, Creep ratio</td>
<td>Signs of seepage, Presence of washed out fines, Animal burrowing, Altered vegetation on bank</td>
</tr>
<tr>
<td>Backfill Washout</td>
<td>Rear of the embankment or the ground behind the embankment is washed away therefore weakening the structure. It can be caused by a number of sources such as excessive seepage through or behind the embankment caused by weak soils and high water levels or deep cracks in the embankment. The presence of foreign objects such as drains or pipes carrying water could lead to washout of the backfill.</td>
<td>Internal void dimensions, Slump dimensions, Crack length, Crack width, Crack depth</td>
<td>Erosion/Slumping of outer slope, crest or ground behind asset. Presence of washed out fines in or around outer slope, Presence of foreign objects (drains/pipes)</td>
</tr>
</tbody>
</table>

* As stated, this is usually not considered to be a failure but is included for completeness

3.3 Surface condition appraisal and monitoring

In order to assess the effects of the performance features detectable on the surface of the embankment some reference or relationship to the relevant performance models is obviously needed. Table 1 provided examples of the performance parameters related to the failure modes for an embankment and recent work collating performance models under the EU funded FloodSite programme (Allsop et al, 2006) was utilised to identify these quantitative measures needed to assess performance. Specific examples for key visual performance indicators related to asset performance and failure are given in the following sub-sections.

It is important to note that accurate assessments of embankment dimensions are required for many of the performance models. This emphasises the significance of...
those methods and technologies that can provide such quantitative assessment of asset surface geometry such as LiDAR, Photogrammetry or other terrain surveying techniques. One specific feature of embankment geometry, crest height, is of critical importance as it is intrinsically linked to the standard of protection offered by the embankment. This is discussed in more depth in section 3.3.1.

In addition to asset geometry, quantification of surface features and visual indicators of potential failure are critical to any introduction of quantitative assessment for embankments. Table 2 lists the major visual indicators, describes them and gives their likely location on the asset. It also provides physical dimensions for slight, minor and major occurrences of each. These definitions were developed and agreed in consultation with steering group members and expert collaborators. However, it should be noted that the severity of defects strongly depends on the local situation. Values given should therefore be taken as illustrative. In terms of the dimensions shown X represents the value parallel to the embankment crest line, Y represents the value horizontally perpendicular to the crest line and Z is the change in elevation associated with the feature. This table will be referred to throughout the subsequent sections of this chapter as it illustrates the size of feature that any inspection method should be able to identify.

Table 2. Surface features related to damage and failure for an embankment

<table>
<thead>
<tr>
<th>Visual Indicator</th>
<th>Location</th>
<th>Description</th>
<th>Dimensions (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>Slight Minor Major</td>
</tr>
<tr>
<td>Rutting</td>
<td>Crest/Slope</td>
<td>Wearing of crest or slope due to traffic (human or livestock)</td>
<td>X:0.1-0.3 Y:0.2-0.5 Z:0.05-0.1</td>
</tr>
<tr>
<td>Circular Slip</td>
<td>Slope (either)</td>
<td>Semicircular cracking and lowering of slope section</td>
<td>X:0.1-0.3 Y:0.05-0.1 Z:0.01-0.05 SA: 1-5⁰</td>
</tr>
<tr>
<td>Vermin Holes</td>
<td>Slope (either)</td>
<td>Holes in slope caused by vermin. Slight = vole/rat size, Minor=Rabbit size and Major=Badger/Fox size</td>
<td>X:0.05-0.1 Y:0.05-0.1 Z:0.05-0.2</td>
</tr>
<tr>
<td>Slumping</td>
<td>Toe/Crest</td>
<td>Depression at toe or crest. If at toe, there may also be movement of slope above slump leading to a change in slope angle (SA)</td>
<td>X:0.1-0.2 Y:0.1-0.3 Z:0.02-0.05 SA: 1-5⁰</td>
</tr>
<tr>
<td>Heaving</td>
<td>Toe/Crest</td>
<td>Uplift at toe or crest caused by geotechnical or hydraulic issues. May be slumping behind heave point</td>
<td>X:0.1-0.2 Y:0.1-0.3 Z:0.02-0.05</td>
</tr>
<tr>
<td>Cracking and Fissuring</td>
<td>All</td>
<td>Presence of openings in bank and potential movement or erosion at crack or fissure points</td>
<td>X:0.01-0.05 Y:0.001-0.01 Z:Negligible</td>
</tr>
</tbody>
</table>

A detailed inspection would enable the quantification of changes to topography by measuring tools and photography. Repeated measurements of an affected section over time would enable asset managers to confirm whether any geotechnical instabilities were an isolated incident or an ongoing process. This would be useful information in determining an appropriate intervention and deciding whether an invasive geotechnical investigation or remedial earthworks were required.
3.3.1 Crest height

Crest height is of critical importance in terms of the embankment’s performance and the SoP that is offered by the asset. Embankments are designed to provide a specified SoP before any overtopping occurs. The SoP is typically represented by a ‘1 in $x$ years’ or $x$ return period formulation where the asset will be overwhelmed by flooding events (and the corresponding water level) that occur on average once in every $x$ years. Embankments crest levels above the height related to the SoP are defined as the freeboard.

Clearly, accurate assessment of crest levels is essential to asset managers. Early identification of any reduction in the SoP or available freeboard helps avoid the potential for asset failure. Unfortunately a purely visual inspection is not well suited to quantifying crest levels, though it may be useful in identifying local low points along the crest such as those caused by rutting or local settlement.

Methods for surveying crest height both accurately and easily are perhaps the area where the introduction of quantitative assessment into the asset monitoring process would be of greatest use in flood defence asset management. This was an area of particular interest to the project and a range of potential methods for this function was examined through research and experiment.

The two methods most obviously suited to the requirements of this work and the EA’s needs are LiDAR and Real-Time Kinematic GPS (RTK GPS). Both of these methods were examined in some depth through a number of case studies and trials (as described in chapter 8). Aerial photogrammetry would also produce acceptable results for crest profiling but its greatest benefits are in respect of other asset monitoring issues and it will therefore be considered further in later sections (sections 3.3.3 to 3.3.6).

Both terrestrial and mobile laser scanning have potential uses in crest height measurement but generally have practical limitations. Terrestrial laser scanning (TLS) from a tripod can achieve high levels of detail and accuracy but is not an appropriate method. It would also be very slow when only a crest height is required. Vehicular access to embankment crests and travel along them may be an issue with mobile laser scanning (MLS). For these reasons airborne LiDAR surveying has advantages and is the preferred option. If there is walking access along embankment crests, results from trials carried out under this project, showed that RTK GPS is a good solution in most instances. TLS and MLS may be useful in specific areas and may be suitable for detecting small scale deformations that could be lost in a DSM of large grid interval.

The key points in relation to the use of airborne LiDAR for crest profiling embankments are:

- The elevation accuracy of the point cloud produced is normally sufficient, in most instances. Where the accuracy required is critical then helicopter mounted LiDAR, such as the Fli-Map system trialled previously by the EA (Burgess, 2004) may be more appropriate.
- The grid size of the DSM produced may be an issue in embankments with narrow crests. Generally, grid size should be less than crest width (ideally it
should be half the crest width or less) if crest height is to be accurately assessed. With grid sizes equal to or greater than the crest width, the interpolation of the point cloud to the ‘gridded’ DSM will potentially include slope elevation values in the grids representing the crest thereby reducing the elevation value calculated for the embankment crest. It is now possible to get grid sizes as low as 25cm or even 12.5cm if necessary.

- The point density produced by modern laser scanners is more than sufficient for the purposes of crest profiling of earth embankments. Anderson (Anderson et al, 2005a) discusses the relationship between point density and elevation accuracy in more detail than is needed here. Point density is however, more critical in terms of fault detection as discussed in sections 3.3.3 to 3.3.5.

- The vegetation cover (and other surface obstructions) can affect elevation accuracy. LiDAR is capable of penetrating light vegetation but significant cover such as trees or shrubs will produce misleading assessments of surface elevation. This is not generally a major issue in flood defence embankment profiling as EA guidelines tend to limit vegetation near and on embankments where possible. However, exceptions exist (see Silverdale case study in section 7.3 for example) and should be considered when planning to utilise LiDAR for crest profiling. Terrestrial based surveying alternatives may be required for those areas where vegetative cover is a significant obstruction of the bank crest from the air.

![Figure 3.2. LiDAR DSM showing presence of trees on terrain (deformations to terrain on the left of the image)](image)

- The coverage of airborne LiDAR is excellent and enables the rapid acquisition of crest profiles that would take considerable time and effort to profile from terrestrially based alternatives. This is because, unlike rail or highway infrastructure embankments, there is not always a readily available access point for ground vehicles near flood defence embankments.

- Processing the DSM to produce a crest profile for a bank can be a resource intensive process and automation cannot be relied upon. The processing required will be heavily determined by the accuracy of profile needed and location specific factors such as the presence of any structures near the embankment which could make identification of the crest difficult. Crest profiling of the Tidal Thames under the Thames Estuary 2100 (TE2100) project highlighted the difficulty in generating crest profiles from LiDAR data where embankments are co-located to industry and housing (Scott et al, 2005).
RTK GPS is a well established method used in land surveying and construction. A roaming GPS receiver is used to survey a site. This GPS receiver could be pole, vehicle or backpack mounted. Differential corrections from a fixed point GPS station (reference station, or network of stations) are used to reduce the positional errors to 1-2 centimetres (using dual frequency survey grade receivers with open sky). Real time communication between the roaming unit and the fixed station or network is necessary. This is usually achieved through the use of mobile phone (GSM/3G) networks or a radio transmitter/receiver. The technology is already used by some EA Asset System Management (ASM) teams to profile crest height (e.g. Midlands East region regularly employs RTK GPS with a surveying pole).

A number of trials carried out (see section 7.3) confirmed that RTK GPS could be used for successfully profiling embankment crests and identified best practice to balance profiling efficiency with elevation accuracy. Key points arising from these trials and research carried out are:

- RTK GPS positional accuracy is more than sufficient for asset management purposes and produces crest profiles of superior accuracy to LiDAR in many instances.
- Coverage is very low in comparison to LiDAR as it only measures a single point/profile for each pass of the equipment. In addition, the operator needs to ensure that path chosen represents the embankment crest. This means that it might be necessary to perform a number of passes to ensure that a fair representation of the crest has been profiled.
- All GPS requires a clear view of the sky and any obstructions to this will reduce accuracy or even result in no positional assessment (see Silverdale case study in section 7.3 for example). Examples situations where this will be important are in ‘urban canyons’ where high buildings are present or under heavy vegetation such as trees.
- Dual receiver base RTK GPS (where a roaming and fixed point GPS receiver linked by radio are utilised) requires a minimum of two staff to operate as one needs to stay with each receiver.
- RTK GPS utilising mobile phone networks to link to a fixed GPS network (e.g. Ordnance Survey’s OSNet) only requires a single operative. However, it obviously requires a mobile phone signal and may not be of use in remote areas with poor mobile phone reception.
- Vehicle based RTK GPS is employed across a range of industries, in particular the agricultural industry to monitor crop seeding or fertilising. Flood defence embankments are mowed regularly by EA Ops Delivery teams as part of their management. RTK GPS could be easily mounted on mowing equipment and could be used to profile the entire embankment surface during the mowing process. This would represent a significant efficiency saving over foot-based methods and would produce profiles of the entire embankment surface rather than just a few passes over or near the crest. A number of logistical and operational obstacles may need to be overcome but the potential benefits (efficiency without loss of accuracy and massively increased coverage) make this solution very attractive from an asset management perspective.
- The use of a survey pole produces high accuracy but can be slow as it may be beneficial to stop regularly at fixed points to take readings.
• A surveyor’s wheel can be used to reduce the need to stop and survey at fixed points along the crest. The accuracy of profile produced, in tests carried out for this project, was sufficient for asset management purposes. However, it was found that the wheel was difficult to use in heavy vegetation.

• Backpack mounted RTK GPS was found to produce results to an accuracy of approximately 0.1m. This method significantly increased coverage compared with other methods and was considered much easier to use. It is felt that this configuration is most suited to crest profiling of embankments for flood defence monitoring. About 8-10km/day could be profiled using this method depending upon site conditions.

• As with all GPS, poor atmospheric conditions could affect accuracy but this is unlikely to be a significant issue.

### 3.3.2 Cracking

Cracking of an embankment’s surface can be both a sign of potential failure and a natural seasonal process. It is important to distinguish between the two. However, some cracking associated with the drying out of an embankment can be a performance issue. In certain soil types it can be indicative of a failure mode, fine fissuring (FRMRC phase 1 work package 4.1). Typically, cracking of significance to performance is of a deeper nature and may be associated with other surface deformations such as those shown in Table 2. Tension cracks (see Figure 3.3) are a particular concern as they are one of the initial surface features for slope instability. The recent, *Earth Embankments: A good practice guide*, describes the significance of tension cracks in terms of embankment condition.

*The formation of large tension cracks more than 5mm wide may be indicative of more immediate problems (deep-seated slip failure or differential settlement caused by embankment raising). If left untreated, such cracks will lead to further deterioration. However, the underlying cause of the cracking must be established before the cracks themselves are treated or the cracks will just reappear.*

(Morris et al, 2007 p150)

![Figure 3.3. Tension cracks in a slope [from CIRIA, 2003]](image-url)
Cracking (in flood defence embankments) is generally due to a very small scale deformation of the asset (see Table 2) and would not be detectable above the asset level of monitoring (see section 2.8). It would therefore be undetected by most remote measurement methods, particularly the vehicle mounted methods which may be used in asset monitoring. The monitoring of cracking is therefore most suited to assessment with standard measuring tools (such as tape measures, rulers and crack gauges) or with close up photography. In the future, geo-referenced or fixed point photography is likely to be the preferred option as this enables quantitative data to be extracted from a photograph. Currently however, the combination of measuring tools and photography provides a good balance of quantitative assessment and visual record. Photographic rulers (see Figure 3.4) could be useful in this regard.

Cracks should be assessed in terms of their length, width and depth. It is difficult to relate a single absolute measurement to likely asset performance but relative assessments over time can be used to identify any change in crack dimensions or propagation of cracks across the asset’s surface. This information would then feed into the next step of asset management – performance assessment.

Figure 3.4. Example of photographic rulers (elasbrno.cz)

3.3.3 Slumping/rutting

Slumping or rutting are both visual indicators of damage to an embankment or the ground surrounding it. Their cause and role in performance are fundamentally different but from a monitoring point of view they are similar. Both represent a lowering of the ground in a particular area and for slumping there may be the presence of cracking around the lowered section.

Slumping can be caused by a range of geotechnical faults in the embankment or its foundation soil. Its presence is often a sign of internal instability (see Table 1) though it could also be caused by the presence of internal voids caused by backfill washout or vermin burrowing.

Table 2 gives quantitative details for slight, minor and major slumping in an embankment. The dimensions of slight slumping would only be identifiable at the asset level and would be difficult to detect under significant grass cover. It would also be unlikely to be detected by purely visual inspection. It may be detectable by comparing previous measurements taken or by photography. Associated cracking is
likely to be the primary discriminator of slight slumping. Minor slumping would be hard to detect with remote measurement (unless done at the asset level using a method such as TLS) since the depth of the surface deformation is within the error margin for most remote measurement methods. If surface vegetation was minimal it may be possible to detect minor slumping on a LiDAR DSM of sufficiently high accuracy and resolution (e.g. helicopter/ground vehicle mounted, grid size 0.25m or less). Minor slumping should be detected by visual inspection, comparison of asset photography or through basic measurement tools, again assuming surface vegetation is not of excessive length. Motion sensors such as accelerometers would detect minor slumping assuming that the sensor was installed in or around the slumped section. Inclinometers could detect any change in slope angle caused by slumping as would Time Domain Reflectometry. Minor slumping can also be quantified by survey levelling or total station measurements.

Major slumping should be evident to all relevant monitoring methods and sensors assuming that excessive vegetation does not obscure the bank surface. LiDAR resolution (DSM grid size) would need to be smaller than the extent of slumping (a number of points must lie on the slump) to get an accurate assessment of the slumped section with LiDAR.

Rutting is a lowering or removal of a section of the embankment caused by third party damage. Typically this is caused by the repeated passage of people, animals or vehicles across a section of the embankment leading to the removal of any grass cover and subsequent erosion of the embankment material. Rutting could occur anywhere on an embankment but is most typically seen at the toe or crest. Figure 3.5 shows the rutting near the crest of an embankment where grass cover has re-grown illustrating that, if the third party damage is removed or reduced, grass cover can re-grow over the rutted section.

![Figure 3.5. Rutting of an embankment crest](image)

Monitoring of rutting is similar to that outlined for slumping except for the fact that any vegetative cover is likely to be minimal or not present due to the fact that rutting is caused by surface traffic which will wear away the cover. This should make the task of identification easier and since rutting in general does not occur suddenly, in general one would not expect to need sophisticated equipment to assist standard visual inspection to detect or monitor rutting. However, the patches of bare earth associated with rutting make it well suited to detection by photogrammetry. Near IR
photogrammetry will be particularly effective due to the way by which vegetation is highlighted in the imagery produced. When vegetation cover exists on a rutted section monitoring will be as for slumping except that there will be no cracking evident.

3.3.4 Heaving / uplift

Heaving or uplift is caused by geotechnical problems such as slope instability or triggered by hydraulic pressures within the embankment. The embankment surface is raised at the crest or the toe of the embankment. The uplifted section will often lead to corresponding localised slumping near the raised section. Cracking can often be seen around the uplifted section if not obscured by grass cover.

Monitoring of heaving / uplift in the slight / minor / major categories broadly is similar to that discussed for slumping or rutting (except for detecting raised rather than lowered sections of the embankment). The use of remote measurement methods when grass cover is minimal (i.e. just after mowing) should maximise the chances of detection. The fact that heaving is restricted to the crest and toe combined with the chance of associated slumping makes this condition indicator more easily monitored. As with slumping, slight heave will be difficult to identify except through close photography or investigation of the affected section. Major heaving should be identified through many of the methods outlined. Minor heaving or uplift, like minor slumping, require favourable conditions and high resolution remote measurement methods. It should be detected by visual inspection, motion sensor or fixed camera (if within its field of view).

3.3.5 Slipping / sliding

Slipping or sliding is a surface indicator of slope instability commonly caused by internal geotechnical processes in the embankment or underlying soil. Third party damage or activity could also lead to slope instabilities and the appearance of slips and slides in the slopes. Bromhead (Bromhead, 2001) describes the various types of slip or slide that can form and the geotechnical processes involved. It should be consulted for detailed technical information. There is a range of types of slips (e.g. circular, rotational, deep seated, translational) and their appearance reflects the underlying geotechnical process occurring. Error! Reference source not found. shows a large circular slip in an embankment slope [see section 7.3.4 for further details of this specific fault].

Steeper slopes are less stable than shallower ones. They are also more prone to slipping or sliding and more rapidly progress to failure and potential breach. Accurate assessment of slope angle is therefore useful and another area where quantitative assessment of asset geometry would provide benefit to asset managers. Table 2 classified circular slips into slight / minor / major categories with estimated dimensions for each. This classification would also apply to other types of slipping or sliding and can be used to assess appropriate monitoring options for each category. Slight slipping would be unlikely to be detected by anything other than close and detailed inspection. Minor slips could be detected by visual inspection or motion sensors but would be difficult to detect by LiDAR due to the limited changes in
elevation which occur. High-resolution photogrammetry would be the remote measurement method most likely to identify slipping in a slope as it provides a detailed image of the asset surface and the edges of the slip would be visible (assuming grass cover is short). Stereo photogrammetric coverage would potentially allow for the quantification of the slip.

![Figure 3.6. A large circular slip in an embankment. Left – close up. Right – view from embankment toe](image)

3.3.6 **Deterioration of surface protection**

Earth embankments used for flood defence traditionally employ grass cover to protect against erosion. The protection offered is dependent on the quality and length of the grass cover, its substrate and the erosion resistance of the core. Ideally, grass should cover 100% of the embankment unless replaced by other surface protection materials (e.g. tarmac pavement on the crest to allow for heavy traffic or concrete revetment on the inner slope to reduce erosion by wave action or erosive current). Bare earth should not be present as it will erode quickly due to water run-off, wave action or channel current.

In addition to just providing coverage, the *quality* of the grass is critical to the level of protection that it offers the embankment. In terms of slope protection, quality is determined by the length and variability of the grass cover. Shorter length grass is preferred to enable better visibility of the embankment for a visual inspection.

Monitoring the condition of embankment grass cover is currently achieved satisfactorily under visual inspection. Quantitative assessment of any loss of cover at the asset level could be useful to track change over time but a rough estimate of cover is probably sufficient. Continuous monitoring of embankments with fixed cameras at random or key points would be a better tool for assessing seasonal changes to vegetation and could be used to intelligently determine optimal mowing conditions. However, it is remote measurement (through photogrammetry, near IR photogrammetry and multi/hyperspectral imaging) of the area where monitoring of embankment vegetation is most likely to provide efficiency benefits to asset managers.

Airborne or satellite imaging systems can highlight embankment vegetation at the system or reach level and can indicate any anomalies in coverage (e.g. bare earth or local changes to vegetation type and structure due to wetter or drier ground) over a wide area. This could then be used to ensure that inspections are focussed more
efficiently on assets where anomalies have been already identified and to build up a seasonal model of the vegetation present for the embankments in the asset system.

Deterioration, failure and condition assessment related to surface protection materials other than grass can be found in the discussion of sloping revetment assets (section 6.2).

### 3.3.7 Large scale settlement or movement

Natural settlement over time is to be expected with any large infrastructure asset such as an embankment. However, local or regional ground conditions or poor embankment design can lead to excessive degrees of settlement over an embankment or entire asset system. Ultimately this can lead to a reduction in crest height increasing the likelihood of flooding and therefore flood risk. Of particular concern, rapid or differential settlement across embankments can also be the underlying cause of slope instability. This can manifest itself in slumping, heave, slipping and cracking of the embankment.

Detecting large scale settlement or movement without the presence of the visual indicators described so far (e.g. cracking or slumping) through visual inspection is difficult if not impossible. Remote measurement and continuous monitoring offer the best solutions for detecting this type of geotechnical fault or land movement. Where individual assets are thought to be prone to settlement, the installation of motion or positional sensing equipment may be beneficial. Settlement typically occurs gradually over a long time period and would require motion sensors capable of detecting very small movements or positional sensors capable of high levels of accuracy (see table 2).

For large scale settlement affecting a group of assets at the reach or system level, fixed GPS networks have been identified as a potential solution. The BigF project (Bingley et al, 2005) demonstrates how a fixed network of very accurate GPS receivers can be used to assess changes in ground levels to very great accuracy. More recent work arising from this and focussed on the Thames estuary has shown how a network of GPS stations can be combined with InSAR data to accurately monitor land level changes within the context of flood risk management (Bingley et al, 2008).

System and reach level remote measurement methods are another possible method for monitoring large scale settlement. Radar based technology such as InSAR can be effective in this regard due to its ability to detect change, and therefore land movement (Bingley et al, 2008). High altitude or space-based radar systems can monitor an entire asset system or catchment at regular periods and detect signs of land movement such as those caused by local geotechnical conditions or due to third party inference (e.g. land subsidence caused by mining). Results obtained illustrate change rather than absolute elevation and this latter should be confirmed through topographical survey (e.g. Airborne LiDAR or ground survey).

For accurate, quantitative assessment of settlement of embankments at the reach/asset level, airborne LiDAR or ground-based surveys are the primary method available. LiDAR is the more efficient for a reach or sub-reach but has its limitations, as
discussed in section 3.3.1. Where only a small group of assets are affected within a
localised area, ground based surveying methods such as RTK GPS, robotic total
stations or simply levelling may be best suited to quantitatively assess any settlement.

Due to the difficulties in assessing large-scale settlement through visual inspection,
this is an area, like assessing crest height, where quantitative methods would excel
and provide asset managers with critical knowledge not easily available under current
flood management practices.

3.4 Subsurface failure indicators and monitoring

As stated in previous sections, many embankment failures are initiated by subsurface
conditions that are not assessed by visual inspection. Most of the surface features
described in section 3.3 are visual indicators of subsurface processes and are not
detectable until deterioration below the surface of the embankment has progressed to
affect the surface. Detecting subsurface conditions prior to the appearance of these
surface indicators would be highly beneficial and would enable earlier intervention.
It may also detect impending failures that cannot be identified through assessment of
the embankment surface.

Most subsurface or geotechnical investigations are invasive techniques requiring the
use of boreholes and trenches. This section investigates non-invasive methods only or
those that offer minimal intrusion (such as the installation of monitoring sensors).
Geophysical methods such as Ground Penetrating Radar (GPR) or Electrical
resistivity tomography (ERT) are non-intrusive but may not provide high enough level
of accuracy and require expertise to interpret the results. Remote measurement
methods can also be used to infer subsurface conditions though ground based
investigation would be required to confirm any conditions of concern.

Principal subsurface failure indicators are described in the following sections along
with a brief discussion of their effects and how they could be monitored.

3.4.1 Presence of internal voids

The presence of internal voids within an embankment or in the underlying ground can
initiate or accelerate a number of failure modes (e.g. slope instability, backfill
washout and piping). Any change to the number or size of voids is an issue of critical
concern and could be a prelude to major failure and breach of the embankment.
Specific causes for voiding are not of great relevance here but could include poor
construction, local geology or damage caused by burrowing animals.

There are a number of potential methods capable of identifying voids within an
embankment or its foundation but GPR is the principal method relevant to the
requirements of flood embankment monitoring. It is capable of detecting subsurface
features to a depth of approximately 15m. However, its penetrative capability is
reduced, sometimes to only a few centimetres, in the clayey, saturated soils which are
typical for flood defence embankments. Though effective at identifying voids, GPR
can often generate false-positives and should be used with care by a trained expert.
As part of the recent EU funded Floodsite project, a method for GPR more suited to
flood defence embankments was described (Impact Geogroup, 2008). Research
suggests that this would seem to be the best solution, at present, for internal void monitoring and further research of this technology in the UK is recommended.

There is a range of other geophysical methods capable of subsurface investigation, e.g. gravity gradiometry, aeromagnetic surveying and seismic reflection, but these are intended for analysing rock and soil types at much greater depths than is relevant to flood defence monitoring. They do not offer the same accuracy as GPR at shallow depths and are primarily used in oil and gas exploration. However, they may therefore be of some use if asset managers thought that geotechnical issues were being caused by undiscovered geological faults deep within the ground.

### 3.4.2 Soil permeability

The permeability of the soil within or under an embankment is an important physical property used in many of the performance models for embankments, particularly those relating to seepage, piping and internal erosion. Differences in permeability between the embankment fill and the foundation soil can lead to differential hydraulic loading and potential failure due to the increased pore water pressure in the soil. The recent Floodsite report, *Failure mechanisms for Flood Defence Structures* (Allsop et al, 2007), provides a detailed explanation of the role of soil permeability on performance along with the associated equations.

![Figure 3.7. Changes to embankment resistivity over time [source: Rowsell and Owen, 2009]](image)

Electrical resistivity tomography (ERT) or electrical resistivity imaging (ERI) is a geophysical method which measures the electrical resistance of an embankment at...
various points on its surface. Results obtained can be used to infer the type and nature of the soil conditions due to the difference in electrical resistance between soil types. For example, clay has a very low resistance (1-20 $\Omega$m) whereas gravel has a relatively high resistance (300-2000 $\Omega$m). Moisture content greatly affects the resistance value of the material and this repeated use and calibration of this method can be used to assess the permeability of the embankment and its moisture content.

3.4.3 Internal seepage

Seepage inside or underneath an embankment can lead to a piping failure or blowout (Terzaghi and Peck, 1967) of an embankment. This type of failure is a particular concern as it can occur without warning under high loading conditions. Piping failures accounted for an embankment breach during the 2007 summer flooding events in the UK on an embankment that had been recently visually inspected and assessed as being in good condition.

Seepage is generally a feature encountered in specific soil types. Certain areas such as the Lincolnshire Fens in the UK or numerous regions in the Netherlands are prone to internal seepage due to the local soils. It is in these areas where particular attention is, and should be, focussed on detecting seepage and potential piping failures for embankments.

The ability to monitor internal seepage is therefore an area of importance. The principal means for detecting internal seepage without the presence of surface indicators, such as the pooling of water at the toe or ground around the toe is through the use of moisture sensors. Piezometers can be used effectively in this regard but require installation within the embankment, an invasive process.

Remote measurement by Near IR photogrammetry or InSAR can also be useful in detecting areas of saturation at the surface indicating seepage. However, uncertainty in the results obtainable by these methods limits its usefulness. Where such survey data exists it could be analysed to confirm or clarify results obtained from more accurate methods or visual findings.

LiDAR can also be used to identify terrain features such as drainage channels or low points in the terrain, areas where seepage is most likely to occur. A case study provided by a geotechnical engineer from Halcrow plc is included in section 7.4 to exemplify the potential for aerial remote measurement in predicting subsurface seepage in embankments. Other methods such as those which consider soil type and moisture could help where these old channels do not register in surface elevation.
4 Vertical walls (Gravity)

This chapter examines vertical wall flood defences that rely on their mass for stability and function. Gravity walls are commonly used in urban and suburban environments and are typically constructed of concrete, stone or masonry. The content of this chapter will focus on how their quantitative monitoring can be achieved and where it differs from the methods and techniques outlined for earth embankments.

4.1 Gravity walls – performance, deterioration and failure

Gravity walls used as flood defences can be broadly categorised into two design types: raised and retaining walls. Raised walls are the principal type discussed in this chapter and consist of an inner and outer face with a crest some height above ground level. A retaining wall will usually have little or no crest above the ground level and its role is to retain soil and prevent the ground behind the wall from eroding due to wave action or current. Gravity walls aim to provide an impermeable barrier between source and receptor and to retain high water levels to a specified SoP. The wall’s mass is designed to ensure that it can withstand hydraulic loads up to (and over) its crest height. Foundation, material and any joints between wall sections are critical elements in the performance of a gravity wall flood defence.

4.1.1 Failure modes, deterioration processes and their visual indicators

Table 3 shows the main failure modes, performance parameters and associated visual indicators for gravity walls. It is not intended to be an exhaustive description of potential failures but instead is focussed on those found to be relevant to key failure modes identified in previous work (Long et al, 2006).

It is important to note that failure modes are not mutually exclusive and in fact it is typical for a convergence or cascade of failure modes to occur. For example, Deterioration of material/collapse is often an initiator of backfill washout or overturning. Also, backfill washout and piping are often commonly found to occur in the same asset due to geotechnical issues in the underlying soils. Visual indicators may also be shared across failure modes and may not be sufficient to uniquely identify a particular failure mechanism.
Table 3. Failure modes, performance parameters and visual indicators for gravity walls

<table>
<thead>
<tr>
<th>Failure Mode</th>
<th>Description</th>
<th>Performance Parameters</th>
<th>Visual Indicators</th>
</tr>
</thead>
<tbody>
<tr>
<td><em>Non-structural failure (overtopping)</em></td>
<td>Flooding occurs without breach of the defence due to water level exceeding</td>
<td>Water Level</td>
<td>None</td>
</tr>
<tr>
<td></td>
<td>the crest height</td>
<td>Crest Height</td>
<td></td>
</tr>
<tr>
<td>Translational Sliding</td>
<td>Wall or wall section moves laterally due to hydrostatic pressures under</td>
<td>Slide length</td>
<td>Misalignment of wall sections</td>
</tr>
<tr>
<td></td>
<td>loading. Retaining wall could be laterally displaced due to pore pressures</td>
<td>Wall weight</td>
<td>Cracking/slump/heaving in ground behind wall</td>
</tr>
<tr>
<td></td>
<td>in earth retained.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Rotational Slip</td>
<td>Wall rotates about the toe with the crest tilted outwards and toe slipping</td>
<td>Slab length</td>
<td>Scour at toe</td>
</tr>
<tr>
<td></td>
<td>inwards. This will eventually lead to collapse of the wall unless the</td>
<td>Ground levels</td>
<td>Misalignment of wall crest</td>
</tr>
<tr>
<td></td>
<td>structure is stabilised. Typically caused by scour of ground around the</td>
<td>Crack Width</td>
<td>Heaving in ground behind wall</td>
</tr>
<tr>
<td></td>
<td>toe of wall.</td>
<td>Crest Angle</td>
<td>Cracking in wall or ground behind wall</td>
</tr>
<tr>
<td>Overturning</td>
<td>Wall leans inwards towards the source (fluvial/coastal). It left unchecked</td>
<td>Wall width</td>
<td>Misalignment of wall crest</td>
</tr>
<tr>
<td></td>
<td>this can lead to the wall toppling into the source. Cracks may form in the</td>
<td>Ground levels</td>
<td>Slump in ground behind wall</td>
</tr>
<tr>
<td></td>
<td>or the ground around the toe. Ground may display signs of slump behind wall.</td>
<td>Crack Width</td>
<td>Cracking in wall or ground behind wall</td>
</tr>
<tr>
<td></td>
<td>For retaining walls could be caused by excessive pressure in retained earth.</td>
<td>Crest Angle</td>
<td></td>
</tr>
<tr>
<td>Bearing Capacity</td>
<td>Wall sinks under its own weight due to poor design and/or geotechnical</td>
<td>Slab Length</td>
<td>Lowered wall sections</td>
</tr>
<tr>
<td></td>
<td>weaknesses in foundation soils. This leads to a reduction in crest height and</td>
<td>Ground levels</td>
<td>Cracks in wall</td>
</tr>
<tr>
<td></td>
<td>eventually to a reduction in the SoP provided.</td>
<td></td>
<td>Cracking of ground behind wall</td>
</tr>
<tr>
<td>Backfill Washout</td>
<td>Water seeps through or under a wall under loading. This leads to washout of</td>
<td>Void size</td>
<td>Heave in front of toe</td>
</tr>
<tr>
<td></td>
<td>the backfill material and the generation of voids in ground behind the wall.</td>
<td>Hole size and location</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Wall stability is compromised leading to eventual failure or collapse. This</td>
<td></td>
<td>Presence of washed out fines</td>
</tr>
<tr>
<td></td>
<td>is particularly applicable to retaining walls.</td>
<td></td>
<td>Holes in wall</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Signs of seepage</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Presence of voids in ground around wall</td>
</tr>
<tr>
<td>Piping</td>
<td>Water seeps underneath a wall through the foundation material. This leads</td>
<td>Seepage length</td>
<td></td>
</tr>
<tr>
<td></td>
<td>eventually to the of a pathway for water to flow under wall. Water will</td>
<td>Creep ratio</td>
<td>Signs of seepage</td>
</tr>
<tr>
<td></td>
<td>pool at a low point behind the wall (often at the toe). Under high loading</td>
<td>Water level</td>
<td>Presence of washed out fines in ground behind wall</td>
</tr>
<tr>
<td></td>
<td>this can lead to the blowout of underlying soil and collapse of the wall.</td>
<td>Groundwater level</td>
<td>Presence of voids in ground around wall</td>
</tr>
<tr>
<td>Deterioration of material / Collapse</td>
<td>Wall material becomes compromised due to environmental conditions, age, 3rd</td>
<td>Wall Thickness</td>
<td>Decay of wall material</td>
</tr>
<tr>
<td></td>
<td>party interference and/or poor construction. Nature of deterioration</td>
<td>Crack Length</td>
<td>Cracking of wall material</td>
</tr>
<tr>
<td></td>
<td>dependent on material e.g. concrete – spalling, cracking.</td>
<td>Hole size and location</td>
<td>Loss of material at joints</td>
</tr>
<tr>
<td></td>
<td>Will lead to eventual failure and often is a symptom or cause of other</td>
<td></td>
<td>Presence of holes in wall material</td>
</tr>
<tr>
<td></td>
<td>failure modes described.</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

4.2 Surface condition appraisal and monitoring options

The surface condition of the wall and surrounding ground can be used to identify potential failure mechanisms. Some of the typical visual indicators at the asset surface are shown in Table 3. Quantitative assessment of surface conditions can be
achieved through the methods and techniques outlined for earth embankments. The following section describes where the use of these methods differs from their method of use for embankments, or where alternative options exist.

Asset geometry and any changes to it are a key element of surface condition as was discussed for embankments in chapter 3. Two significant differences with gravity walls are that they are generally smaller and more slender structures than earth embankments (except, perhaps, for some sea walls) and have a much harder and more reflective surface. These two properties can have a large impact on the applicability of techniques. The surface of a gravity wall makes it easier to detect minor imperfections such as cracking. Quantitative assessment of such imperfections is also a simpler and more accurate procedure as there is no grass cover to occlude the surface meaning that surface damage is more evident. However, it is important to distinguish between damage affecting performance and deterioration or damage caused by natural ageing processes which is unlikely to affect asset performance.

Another key difference is that the inner and outer faces of a wall typically have a slope angle at or nearing 90°, and any change to this is highly significant in terms of potential performance under loading. Simple measurement and levelling tools can therefore be of great use in the quantitative assessment of walls. Reference marks and tell-tales on the asset can be easily placed and used to monitor changes over time. Potential options for surface assessment by remote measurement, continuous monitoring and detailed inspection are given in the following sections.

4.2.1 Remote measurement

The utility of aerial remote measurement is limited by the dimensions of the wall, the accuracy of the sensing equipment and the resolution of the processed data. Walls can be difficult to identify from a top-down aerial survey as they offer their narrowest dimension from that viewpoint and the two faces of the wall are not clearly visible. An oblique viewpoint offers greater potential. Both the crest and a face of the wall can be monitored but a repeat pass of the aircraft will be necessary to obtain a clear view of both faces.

Terrestrial remote measurement will provide the best view of the faces of the wall but will also require each face to be separately assessed. A terrestrial option may also be limited in its assessment of the crest, depending on the position of the ground-based equipment relative to the dimensions of the wall. It may be necessary to separately monitor the crest which would obviously increase the time and cost of the process. Other limitations of terrestrial based remote measurement over airborne versions, such as access and time required, apply. However, since walls are generally used in urban/suburban locales and their average length is usually less than that for embankments, terrestrial monitoring options can be more practical than for embankments.

As with embankments, LiDAR can be used to rapidly and accurately assess asset geometry. The more reflective, less obscured surface will enable increased positional precision but the reduced cross-section will require a higher resolution DSM in most instances. In order to identify the crest, the DSM resolution will need to be less than
the crest width and for accurate assessment of crest height it should be half the crest width or less. For aerial LiDAR surveys this may require a low altitude option such as Fli-Map.

An example of the effect of DSM resolution for detecting gravity walls is shown in Figure 4.1. The 2m gridded DSM shown in the centre of Figure 4.1 does not show the geometry of the wall only the raised bank on which it sits. The wall can be clearly seen in the 25cm gridded DSM shown on the right. Note that the surveys were flown within a few weeks of each other.

![Figure 4.1](image)

Figure 4.1. Effect of LiDAR resolution for aerial monitoring of gravity walls (Left = Oblique Photography [source maps.bing.com]| Centre = 2m gridded | Right = 0.25m gridded)

Even when the wall can be clearly identified in a DSM care should be taken to ensure that crest height is accurate. If resolution is greater than half the crest width it is possible that the crest height shown in the LiDAR DSM will be lower than actual height because of the interpolation process. The extent of any reduction will be dependent on grid size relative to crest width and grid placement in relation to the crest. Potentially, crest height could be inaccurate by a large degree (50% or greater). In order to get an accurate assessment of crest height for narrow gravity walls it may be necessary to use the raw point cloud data. As stated earlier, this is not currently a practical solution as the dataset is very large and difficult to analyse over large areas.

Aerial photogrammetry can be used to monitor wall geometry effectively provided that high-resolution imagery is used (e.g. 5cm/pixel). However it should be remembered that the limitations of camera viewpoint might require a number of passes to be made at differing angles to gain a full assessment of the entire wall cross-profile. Top-down imagery can be used to assess crest height to a high level of accuracy even with slender structures such as walls. Research on remote measurement under the initial phase of the FRMRC (Smith et al, 2005) demonstrated the potential for aerial photogrammetry supplemented by manual post-processing (analytical photogrammetry) in assessing slender man-made structures using the example of a church spire in Newark (Smith et al, 2005 p54). As described in this work, analytical photogrammetry can produce an accurate assessment of features for these types of slender structures that can match or even exceed results obtained from airborne LiDAR surveys.
Oblique imagery can be used to provide high quality images of the inner and outer faces of a wall. It can be used to detect small scale deterioration or damage to the face of the wall that would not be easily identified by other remote measurement options such as LiDAR or Radar. A low-resolution example of oblique aerial imagery taken from Microsoft’s Bing Maps website is shown in Figure 4.1.

Radar-based remote measurement can be more effective in assessing gravity walls due to their more reflective surface in comparison to an earth embankment. Its inability to provide positional information limits its utility but, integrating with fixed and known reference points (e.g. GPS stations), it can be used to detect change or movement to a high level of accuracy as described earlier. Ground-based radar monitoring can be highly effective in detecting change to the surface of a gravity wall. It can achieve a millimetric level of precision but offers no significant advantage over other ground based remote measurement options.

Kinematic GPS can be used in a similar fashion to that described for embankments to profile the crest of the wall. It may be difficult to utilise effectively for narrow walls where the crest cannot be easily traversed by an operative or vehicle. However, an alternate platform for the GPS receiver (e.g. mounted on a short wheeled pole) could mitigate this potential problem.

### 4.2.2 Continuous monitoring

Options for the continuous monitoring of the surface of a gravity wall are generally similar to those already outlined in chapter 3. However, there are some distinctions and some methods that are of specific use for this asset type. Experience from the management of dams and reservoirs offers a range of potential mechanisms for continuous monitoring systems. Due to the extreme consequences of their failure and the regulatory framework associated with their operation and maintenance, the management of these structures tends to be an early adopter of new methods and technologies. Many of these monitoring systems are not cost effective for deployment in the context of flood defence asset management but may be practical solutions for particularly critical assets. Examples include fixed cameras (video and/or photography), surface mounted motion sensors and fixed GPS receivers. A report by the US Society on Dams (USSD) from 2008 details many of the options for monitoring dams through instrumentation (Myers and Stateler, 2008).

A recent CIRIA report (CIRIA, 2008) on the monitoring of concrete structures is relevant to this discussion since a large proportion of gravity walls are constructed from concrete. Also many of the methods and techniques described in the report would be applicable to the masonry or rock-based gravity walls. The report examines monitoring, and in particular continuous monitoring using sensors and instrumentation, in greater depth and detail than is possible here.

Fixed cameras such as those used in the recent Environment Agency trial for monitoring trash screens (see appendix D) would be applicable for regular monitoring of walls outside of the standard visual inspection regime. Appropriate choice and location of camera equipment could enable quantitative assessment of change over
time and would be of particular use where a potentially dynamic failure process is thought to be ongoing.

Surface mounted instrumentation such as tell-tales, gauges or motion sensors connected to telemetry could be used to trigger alarms when a critical threshold is passed. Similar technology is already employed in dam monitoring systems and only cost and logistical issues would limit its use in flood defence management. The relatively small movements associated with the initiation of failure processes, such as overturning or rotational slip, for gravity walls would make them particularly suited to this type of monitoring as these may be overlooked or undetectable through visual inspection or remote measurement. A major advantage of surface mounted sensors over sub-surface monitoring equipment described in section 4.3 is that it can be installed non-invasively. It is therefore highly suited to use on existing assets where invasive installation may be expensive or impractical.

Toe scour is often the trigger for failure of gravity walls and can be difficult to identify through remote measurement or visual inspection as it is below the mean water level. Scour monitoring for coastal seawall defences at Blackpool via submerged accelerometers has been trialled in research by HR Wallingford (HR Wallingford, 2006). It is a relatively low cost and effective method but may need adaptation to work in fluvial channels due to the increased density of soil in comparison to sand. Scour monitors also require careful placement; too deep and scour will not be detected, too shallow and it may be triggered without scour occurring.

4.2.3 Detailed inspection

Detailed inspection at the level of the individual asset could be of particular relevance to gravity wall type flood defences. Wall surface properties make them particularly suited to a range of options ranging from the simple to the highly technical. Measuring and levelling devices can be used in conjunction with fixed reference points marked or attached to the wall to gather accurate measurement of key properties such as wall height, angle or width. Visual indicators of deteriorations such as cracking or material loss can be quantitatively assessed in a similar way and this information can be supplemented by photography, ideally geo-referenced, to document damage or deterioration over time.

In addition to simple measurement and levelling tools such as tape, laser measurers and spirit levels, more complex and highly accurate equipment could be employed for critical assets where initial results of detailed inspection are unclear. This could include standard surveying tools (e.g. Theodolites, RTK GPS and robotic total stations) for accurate assessment of geometry and digital image processing techniques (Laser Shearoscopy, Digital Image Correlation) for highly accurate (<2mm) assessment of surface material changes. These types of surface assessment methods may be suited to being undertaken by expert consultants. However, with training, asset inspectors should be able to carry out basic surveying and surface assessment work.
The ground or embankment surface on which the wall sits should also be assessed, using appropriate methods as described in chapter 3. It is often here that visual indicators of potential failure or deterioration can be found (as described in Table 3).

As with the general description of detailed inspection methods, the major limitation of this approach is that it is a time consuming and labour intensive process. However, it offers a relatively inexpensive mechanism for collecting good quantitative data on asset performance and many of the methods can be carried out by asset inspectors with minimal additional training required.

### 4.3 Subsurface condition appraisal and monitoring

This section describes briefly the options for monitoring the internal condition of the wall itself. The subsurface condition of the underlying ground can be monitored using those methods applicable to earth embankments discussed in the previous chapter. The detection of any voids and/or seepage in the soil underlying a gravity wall is essential for accurate assessment of likely performance.

Methods for monitoring the internal state of the wall itself are dependent upon its dimensions and constituents. The dense materials used in the construction of gravity walls are not easily penetrable using physical probes such as those applicable for earth embankments. The main options for subsurface monitoring investigated are as follows:

- **Acoustic emission analysis** – Measuring the vibratory response of a structure has been a key topic in structural health monitoring. However, the success and accuracy of such methods is a topic of some debate and it is not capable of providing a definitive assessment of current condition. Changes to acoustic response can indicate deterioration and can be tested through a variety of means ranging from simple tools (e.g. Schmidt Hammer for concrete testing) to complex electronic equipment. Despite its limitations, it is relatively simple to carry out and is non-invasive.

- **X-Ray** – Can be used to image the internal structure of gravity walls and is capable of detecting voids, reinforcement and other anomalies. However, limited penetration, health and safety issues related to the use of radioactive sources and logistical concerns in respect of its use on-site for large structures such as gravity walls mean that it is unlikely that it could be used as part of a detailed inspection by in-house staff. GPR is usually considered a better alternative particularly as the commercial availability of x-ray monitoring is very limited.

- **Ground penetrating radar** – GPR can be used to identify voids, cracks and other internal incongruities in a wall. The penetration and accuracy of results can be much greater than for the clayey soils typically used in earth embankments (15m penetration in concrete for example). It can also be used to monitor the condition of steel reinforcement in reinforced concrete structures.

- **Subsurface sensors** – Various types of sensors (e.g. motion and moisture detection) can be installed within the surface of a gravity wall. Motion sensors such as accelerometers or inclinometers could detect any movement in the wall associated with sliding, slipping or overturning. They can also be placed in the earth at the toe of the wall to detect toe scour as described in previous work by HR Wallingford (HR Wallingford, 2006). Moisture sensors can be used to
detect signs of seepage within or under a gravity wall. The main limitations associated with subsurface sensors are: their installation in an existing structure is invasive; their power requirements can be an issue; and their number and placement within the structure constrains their effectiveness. However, for new-build walls in critical locations, sensors are possibly the most effective and efficient means for subsurface monitoring.
5 Vertical walls (Sheet pile)

This chapter summarises potential methods and techniques for quantitatively assessing sheet pile walls used in a flood defence context. It contains a brief description of the asset type and how it differs from the types of asset described thus far. The effect of these differences on the monitoring process is discussed along with potential modes of failure compared to those outlined for gravity wall type structures.

Sheet pile walls are typically found in urban and suburban locations and in both fluvial and coastal locations. Like all walls, they are highly effective in protecting against erosion from current or wave attack (assuming they are correctly maintained). Sheet pile walls are formed from corrugated steel with corrosion protection.

5.1 Sheet pile walls – performance, deterioration and failure

Sheet pile walls used in flood defence are almost always retaining walls. In some instances, the wall may be raised above ground level but this is atypical and even then the majority of the wall’s height will be below ground level on its outer face. This is due to the means by which wall stability is maintained. In this type of asset, stability is achieved by one of two methods; anchor ties or cantilevering. Anchor tied walls employ a number of steel tie rods secured under tension into the ground behind the wall. Cantilevered walls have a portion of their height embedded in the ground on the inner toe of wall. Cantilevering alone is therefore only used for walls of limited height.

![Figure 5.1. Image of a sheet pile wall with concrete capped crest at Newark, Nottinghamshire](image)

Apart from their means of stability, sheet pile walls function similarly to retaining gravity walls in terms of flood defence. They provide an impermeable barrier between source and receptor to a specified SoP determined by their crest height. Sheet pile walls are slender structures usually no more than a few centimetres in thickness. The crest of the sheet pile is typically capped to protect it from damage and to increase stability. A concrete or timber cap is typical (with concrete being the more common and standard approach to modern sheet pile walls). Figure 5.1 shows an example of this type of asset.
5.1.1 Failure modes, deterioration processes and their visual indicators

Modes of failure are in many ways similar to those described for gravity walls though causes, implications and rates of decline may differ. Table 4 gives an overview of the failure modes specific to sheet pile walls, their visual indicators and the performance parameters associated with each.

<table>
<thead>
<tr>
<th>Failure Mode</th>
<th>Description</th>
<th>Performance Parameters</th>
<th>Visual Indicators</th>
</tr>
</thead>
<tbody>
<tr>
<td>Non-structural failure</td>
<td>Flooding occurs without breach of the defence due to water level exceeding the crest height</td>
<td>Water Level</td>
<td>None</td>
</tr>
<tr>
<td>(overtopping)</td>
<td></td>
<td>Crest Height</td>
<td></td>
</tr>
<tr>
<td>Tie/Anchor Failure</td>
<td>Loss of tension or breakage of anchor rods through corrosion or third party interference. The wall is no longer capable of retaining earth and overturns towards the source. This can lead to unravelling of large sections of sheet pile.</td>
<td>Ground Levels</td>
<td>Missing anchor plates</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Tie/Anchor angle</td>
<td>Loose anchor plates</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Tie/Anchor Length</td>
<td>Cracking in ground behind wall</td>
</tr>
<tr>
<td>Rotational Slip</td>
<td>Wall and retained earth rotates towards source. This could be caused by high pore pressures in retained soil or by repeated and rapid changes in water levels.</td>
<td>Ground Levels</td>
<td>Crest of wall alignment</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Distance between tie rods</td>
<td>Slumping behind wall</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Toe level</td>
<td>Anchor head sinking</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Ground Level (inner)</td>
<td>Toe scour</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Ground Level (outer)</td>
<td></td>
</tr>
<tr>
<td>Backfill Washout</td>
<td>Flow of water through sheet pile leads to washout of backfill material. This can lead to voids in the ground behind the wall and eventually to collapse.</td>
<td>Wall thickness</td>
<td>Holes in sheet pile</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Hole dimensions</td>
<td>Gaps at clutches</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Hydraulic loading conditions</td>
<td>Presence of washed out fines</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Extensive corrosion</td>
</tr>
<tr>
<td>Rotation about tie</td>
<td>Wall rotates towards source as with rotational slip. The difference between this and rotational slip is that the rotation is of the sheet pile alone and not the earth behind it.</td>
<td>Ground Level</td>
<td>Misalignment of wall and crest</td>
</tr>
<tr>
<td>(anchored or tied) or toe</td>
<td></td>
<td>(inner)</td>
<td>Movement at toe</td>
</tr>
<tr>
<td>(cantilevered)</td>
<td></td>
<td>Ground Level (outer)</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Toe Level</td>
<td></td>
</tr>
<tr>
<td>Accelerated Low Water</td>
<td>Wall material corrodes rapidly in certain environmental conditions leading to the formation of holes in sheet pile and eventual collapse. A CIRIA report (CIRIA, 2005) explores this issue in depth.</td>
<td>Wall thickness</td>
<td>Signs of seepage</td>
</tr>
<tr>
<td>Corrosion (ALWC)</td>
<td></td>
<td>Corrosion extent</td>
<td>Presence of washed out fines</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Hole dimensions</td>
<td>Holes in sheet pile</td>
</tr>
</tbody>
</table>

5.2 Surface condition appraisal and monitoring

As described, sheet pile walls are generally retaining walls. Where they are used as raised walls they are of limited height above ground level. The outer face, or a large proportion of it, is therefore below ground level and not easily inspected. In addition, it is often difficult to assess the inner face of the wall as mean water level is usually well above the inner toe making access to the inner face limited. For fluvial defences, the wall is usually inspected from the crest and sections of the inner face obscured from this viewpoint can be inspected from the other bank of the channel (where applicable) or from a boat.

5.2.1 Remote measurement

Sheet pile walls are very slender structures and are therefore not suited to high altitude, top-down aerial monitoring. However, the retained earth behind the wall can
be monitored using aerial remote measurement as with earth embankments. This can be used to identify any evidence of high and low points that might be associated with failure or geotechnical issues. Low altitude options for aerial remote measurement may be of greater use, especially if an oblique viewpoint is used to enable assessment of the inner face of the sheet pile wall.

Terrestrial (fixed point or mobile) options are a more appropriate platform for monitoring sheet pile walls using remote measurement. TLS and MLS have both been used to provide an accurate assessment of the condition sheet pile walls and to detect any signs of deterioration. Both should be undertaken at low tide where possible and hopefully include assessment of the inner toe. Terrestrial photogrammetry also has the capability of accurately monitoring changes to wall geometry associated with failure. It also has the additional benefit of providing high-resolution imagery of the wall’s surface. This can be used to quantitatively monitor the extent of any corrosion and the condition of corrosion protection measures.

5.2.2 Continuous monitoring

Continuous monitoring of sheet pile walls can be achieved utilising the methods outlined for gravity walls. Fixed cameras and surface mounted sensors are potential options along with the installation of scour monitors at the inner toe. Access and logistical issues in installation and maintaining of such equipment may be different due to the specific properties and location of sheet pile structures. In particular, the fact that sheet pile walls are under hydraulic loading most, if not all, of the time must be considered.

5.2.3 Detailed inspection

Detailed inspection of sheet pile walls can utilise similar methods and tools to those outlined for gravity walls. Measuring and levelling tools can be used to acquire quantitative measurements of wall features and geometry. Photography (geo-referenced preferably) can be used to record any defects or changes to the wall or retained earth. Damage such as cracking, slumping or heave to the ground can be quantified as for embankments. Concrete crest caps should be assessed for any signs of cracking, misalignment or spalling in a similar manner to that used for the crest of a gravity wall.

Where detailed inspection differs from that proposed for embankments and gravity walls is in terms of assessing the condition of the steel sheet pile and the anchor rods or ties. Holes in the sheet pile or gaps between clutches can be quantified using standard measuring tools and/or photography. These are indicators of poor condition and potential failure especially where they occur at or below the mean water level. Any increase in their extent and occurrence is a significant issue for urgent remedial action.

Corrosion is a concern specific to steel structures and quantification of its presence and extent would be an aid to asset management. Corrosion leads to a reduction in the thickness of the steel culminating in the formation of holes. At this point the asset no longer provides an impermeable barrier to the source and it is therefore failing to
perform its function. Prolonged corrosion will lead to the failure of the asset due to collapse or backfill washout. Figure 5.2 shows a sheet pile wall showing signs of corrosion. Figure 5.3 illustrates the consequences of extensive corrosion in the same sheet pile wall flood defence.

Figure 5.2. Image of sheet pile wall in poor condition taken at Netley Country Park, Southampton, UK (Left – Overview of wall section with concrete walkway at crest. Right – Close of wall deterioration showing corrosion and presence of holes in sheet pile)

Figure 5.3. Example of failure caused by backfill washout of a sheet piled seawall at Netley Country Park, Southampton, UK.

Geo-referenced or fixed-point photography can be used to quantify the amount of corrosion present on the inner face. Increased corrosion can be identified by regular photography of the inner face as part of the inspection process. This can then be used to trigger appropriate remedial action such as the application of corrosion protection paint. Photography could be supplemented by the use of photographic rulers (Figure 3.4) to provide a record of the scale of corrosion present or measurements could be taken with standard measuring devices and recorded as part of the detailed inspection.

Ultrasonic testing can be employed for non-destructive testing of sheet pile structures (Ogunyoye et al, 2004). It can measure the thickness of the wall to an accuracy of around 1mm assuming the wall surface is clean and not obscured. An alternative
method for testing wall thickness non-invasively is Pulsed Eddy Current testing (Robers and Scottini, 2002). It can provide similar levels of accuracy and does not require such strict surface conditions. Both methods have been routinely employed to test sheet pile walls in channels and ports for a number of years. As they require specialist equipment and training both methods are currently carried out by specialist testing consultants. Further research would be needed to determine if it is practical and cost effective for the equipment to be regularly employed as part of the detailed inspection process.

For walls employing tie rods or anchors, a detailed inspection should check that the tie rods are securely in place and that no damage is apparent. Tension meters can be used to confirm that there is appropriate tension in the rod and that breakage has not occurred.

5.3 Subsurface condition appraisal and monitoring

Most of the subsurface monitoring options for gravity walls and embankments also have application for sheet pile walls. The main opportunities for sheet pile walls relate to those differences in performance and failure outlined in section 5.1. Examples of specific options are listed below:

- Moisture sensors – Backfill washout is a major concern due to the slenderness of a sheet pile wall. Moisture sensors in the ground behind the wall can be used to detect early signs of seepage associated with backfill washout. Choice of location and calibration is important to distinguish between seepage through the wall and saturation due to high rainfall. However, long-term saturation due to rainfall is a potential indicator of poor drainage and high pore pressures which could be a trigger for other modes of failure such as rotational slip or anchor failure.

- Tension gauges/sensors – Anchored sheet pile structures rely on their anchor or tie rods for stability. Failure or loss of tension in the rod is a common source of failure in this type of structure. Tension gauges can be installed with the anchor rod or tie. These devices can monitor the tension is the rod and trigger an alarm when the tension drops below a threshold value indicating that the anchor rod or tie is no longer performing its function.

- Like other linear assets, the condition and stability of the toe of the structure is critical to its performance. Sheet pile walls are typically employed in environments with high currents and/or rapidly changing hydraulic conditions. These can lead to scour at the toe. Scour monitoring devices (as outlined for gravity walls in section 4.3) would be of relevance to the management and monitoring of sheet pile walls in the same way as for gravity walls.

Subsurface monitoring of the earth retained behind the wall can employ those methods outlined for earth embankments. GPR, Resistivity and motion sensors all have potential application and would offer similar results and limitations.
6  Revetment/ Slope protection against erosion and other types of flood defence asset

This chapter discusses the potential for quantitative assessment of sloped revetments, also referred to as slope protection against erosion. For the purpose of conciseness the term revetment will be used from this point onwards in the chapter.

Revetments are essentially a layer of armour or protection covering the surface of a slope or embankment. (Plain grass cover on an earth embankment or the bank of a water course is not regarded as revetment.)

Like gravity walls, revetments can be composed of a range of materials. In fact the variety of revetment materials far exceeds the options employed for gravity walls. Revetments can form a rigid or a flexible barrier and can be impermeable or allow water to seep through to the slope below. They can be formed of a single continuous material, consist of a number of units jointed together or be a loose collection of elements held in place by their mass and the toe of the slope.

This wide variety of revetment types can make it difficult to generalise for all options. This chapter will focus on the principal types of revetment used in flood defence whilst also highlighting those types which represent a specific opportunity in terms of quantitative assessment methods. Many of the methods described for embankments and vertical walls are applicable to revetments. Those of most relevance and potential utility will be listed and any significant differences in their application or the likely results will be discussed.

6.1  Revetment performance, deterioration and failure

Since revetment is actually a surface layer on top of a slope or embankment, many of the underlying failure modes and deterioration processes for earth embankments or slopes are also applicable to revetments. The thickness of the armour layer is dependent on the material used and the local environmental conditions.

Due to the large range of revetment materials and the wide differences between them it is important to briefly outline the key types used in a flood defence role. McConnell (McConnell, 1998) gives a more complete description of revetment types, design, performance and potential failure mechanisms than can be included here and a brief outline of failure modes and performance features relevant to asset inspection was included in previous work completed under the initial phase of FRMRC (Long et al, 2006).

6.1.1  Revetment types

Typical materials used in flood defence revetments are asphalt, concrete, riprap, masonry and gabions. For drainage, geo-textiles or granular filters can also be employed underneath the erosion protection. Revetments can be comprised of a single material type or be a composite revetment combining a range of the materials. Figure 6.1 shows an example of a revetment combining concrete, rock and gabions.
In addition to the material used in the revetment, it is important to note the differing methods of construction and how these impact on performance and its assessment. For example, concrete revetment could be constructed from small concrete blockwork, larger precast slabs or in-situ ready mixed concrete. Jointed materials will have the additional issue of joint condition to assess but will be more flexible than continuous materials.

Concrete is a common material for revetments and therefore many of the assessment options described for the material condition of Gravity Walls in chapter 4 can be applicable to concrete revetments.

6.1.2 **Failure modes, deterioration processes and indicators**

Failure mechanisms for revetment defences combine elements of embankment failure (in terms of the slope and underlying earth foundation) with some of the failure modes associated with gravity walls (in terms of material degradation processes and toe scour). Table 5 shows those failure modes relevant from a management and monitoring perspective and includes those used in earlier work for this type of asset (Long et al, 2006). Due to the wide range of revetment types used in flood defence, some failure modes are material specific and some only apply to particular forms of revetment construction. For example joint failure will only apply to jointed materials and third party removal of revetment will only be applicable where revetment is formed of loose material such as Riprap. Other examples of important material specific issues are listed below:

- Concrete slabs: cracking, washout.
- Asphalt: cracking – washout; surface material faults, ozone-driven deterioration, failure through fatigue under repetitive wave pounding.
- Concrete blocks: movement of individual elements due to dynamic hydraulic pressure in filter layer; wash out of 2nd layer or core materials; slipping of top layer.
• Riprap: S-profile, missing elements, failure of filter (wash out of finer elements from 2nd layer).

Table 5. Failure modes, performance parameters and visual indicators for sloping revetment

<table>
<thead>
<tr>
<th>Failure Mode</th>
<th>Description</th>
<th>Performance Parameters</th>
<th>Visual Indicators</th>
</tr>
</thead>
<tbody>
<tr>
<td>Toe Failure</td>
<td>Like other linear assets, the toe of the slope maintains slope stability. Failure or scour at the toe can lead to slipping or cracking of the revetment due to its mass.</td>
<td>Scour Depth, Slope Angle, Mass of revetment, Coefficient of friction between revetment and slope</td>
<td>Slump or heave at toe, Cracking or movement of revetment material</td>
</tr>
<tr>
<td>Uplift/Sliding</td>
<td>Dynamic hydraulic pressure and Geotechnical pressures in subsurface can lead to uplift or movement of a revetment leading to damage to the material and eventual failure to protect against erosion</td>
<td>Slope Angle, Crack size, Pore pressures in soil, Surface deformation, Mass of the revetment</td>
<td>Slump/Heave in slope, Cracking in revetment</td>
</tr>
<tr>
<td>Backfill Washout</td>
<td>Similar to vertical walls, cracks or holes in revetment (at joints or in the material itself) allow water to permeate the structure and lead to washout of fill material. Voids are formed in the backfill material and eventually lead to collapse of the revetment.</td>
<td>Hole size, Crack size, Revetment thickness, Hydraulic load, Condition of filter</td>
<td>Loss of revetment material, Presence of washout out fines</td>
</tr>
</tbody>
</table>

As with other linear assets, the failure modes described in Table 5 are not mutually exclusive. Failure progression in one mode will often be a trigger for other modes of failure. For example, toe failure can lead to cracking and the formation of holes in the revetment material or joints. This can then trigger backfill washout under loading.

6.2 Surface condition appraisal and monitoring for revetment

Surface level monitoring can employ many of the methods and techniques already outlined for embankments and vertical walls. Where differences in their application and results obtainable are of relevance they will be noted in this section of the chapter.

6.2.1 Remote measurement

In terms of remote measurement, revetments can be treated in the same way as an embankment slope with a few key differences. Smooth surfaced revetments such as concrete, masonry or asphalt offer a regular, less obscured and more reflective surface than a grass covered slope. This will enable greater precision and accuracy of results from remote measurement methods.

Irregular surfaced revetments such as riprap or gabions may be more problematic to monitor through remote measurement methods and particularly for aerial LiDAR surveys that employ post processed DSM datasets. TLS or MLS systems will be more effective as they typically utilise the raw point cloud data rather than a smoothed out DSM. This means that the profile of the revetment produced will more closely represent the actual surface of the asset.

Photogrammetry (terrestrial and aerial) will be an effective method for monitoring all types of revetment provided the image resolution is sufficient in relation to the dimensions of the revetment and its component material. The main advantage of photogrammetry in monitoring revetments is its ability to provide accurate images of
surface condition. This makes it possible to identify any movement or change to revetment material, a visual indicator for many of the potential modes of failure. Small movements or loss of revetment material should be evident from the images produced. Obviously, very small scale cracking or gaps in revetment will require very high resolution imagery and may be more suited to assessment by detailed inspection.

Radar-based options will be more effective on the hard, reflective revetment surface than on grass-covered embankments. Their ability to detect change to a high level of accuracy offers a potential method for detecting small-scale movement in the revetment surface that may not be easily detectable to a visual inspection or through other remote measurement options. As described in chapter 2, radar-based monitoring is a common tool in the monitoring of large earth and rock slopes in the quarrying industry. Despite its increased potential in relation to this type of asset, other limitations of radar-based methods discussed in earlier chapters still apply and should be considered.

6.2.2 Continuous monitoring

Fixed cameras could be employed in quantitative assessment of revetment condition. Cameras would offer similar results to those described for embankments and walls but have some significant potential benefits in regard to revetments. In most instances revetment is applied to a single slope, and possibly the crest, providing an area viewable from a single camera position. There is no outer slope or face to monitor as would be the case for embankments or raised walls. In addition, a revetment’s surface is not generally obscured through vegetation (embankment) or in shadow (vertical wall). Imagery produced from a fixed camera, provided resolution is appropriate, would be capable of detecting any movement or loss of revetment material visible at the surface. Cameras are particularly suited to loose revetments such as riprap which would be difficult to continuously monitor using other methods. They can also be of particular value for monitoring post-storm conditions.

For some types of revetment, surface mounted sensors to detect motion or changes to slope angle such as accelerometers or inclinometers would be applicable. These could detect early signs of potential failures and trigger a detailed inspection and consequential remedial action. Surface mounted sensors would not be practical for loose revetment materials such as riprap which are prone to move under loading. As was the case with surface mounted sensors for other linear assets, consideration should be taken in the logistics of their use: placement, telemetry, power usage and protection from environmental conditions and third party interference are all important concerns. Environmental conditions are a particular issue for revetments. Revetments are generally used where hydraulic loading is more extreme; wave action, strong currents and high variance in water levels are common. Any surface mounted sensors must be able to cope with these conditions. It is likely that the lifespan of sensors would be reduced in these conditions and they may need regular maintenance or replacement.

Like vertical wall assets, toe failure has been highlighted as a concern for revetments. Scour monitors could be an effective method for early identification of scour at the toe of the revetment. Their utility for a specific revetment would be dependent on local ground conditions and hydraulic loading. Many revetments, especially coastal revetments, are...
not hydraulically loaded at all times and a detailed inspection or fixed camera may be capable of detecting toe scour without the need for the installation of scour monitors.

### 6.2.3 Detailed inspection

A detailed inspection of a sloped revetment would combine the method outlined for earth embankments with elements of the method described for gravity walls. Measurement of key performance features such as cracking or any gaps in the revetment combined with geo-referenced or fixed point photography would enable quantification of current condition and any changes to condition that could be quantified in future inspections.

An option not requiring the use of expensive technology and specialist training would be to employ markers and reference points painted or drawn onto the surface of the revetment to monitor and quantify change or movement to the surface material. This was discussed in section 4.2.3 in relation to gravity walls but is perhaps even more useful in the context of sloped revetments. Their variety of material types and structures (e.g. loose, blockwork, slabs, cast in-situ) can produce an irregular surface that is not easily measured with traditional measuring and levelling devices.

### 6.3 Subsurface condition appraisal and monitoring for revetment

As described, a revetment is primarily a layer of surface protection against erosion and as such most of the subsurface of the sloped revetment is identical to an earth embankment slope. Therefore subsurface monitoring options for revetment include those described for earth embankments. GPR, ERT and subsurface sensors can all be used to quantify the internal condition of the soil slope under the revetment. However, soil penetrometers will obviously be of little use for sloped revetments.

In terms of the revetment material itself, GPR and material specific NDT methods outlined for gravity walls will be capable of monitoring their internal structure. The interface between revetment and underlying soil slope is the area where monitoring should focus. Damage, movement and the presence of voids in this region can lead to slipping of the revetment cover and to eventual failure. Where drainage and filter layers are present, damage could be indicated by increased saturation at the interface. Internal moisture sensors could be used to detect this and could be installed during the construction of the revetment.

### 6.4 Miscellaneous flood defence asset types

This section covers other asset types that were investigated during the project but are outside the scope of the main aims and objectives of the project, namely, to investigate quantitative assessment for the principal forms of linear flood defence asset. Information on these assets was not actively sought but became evident during the research programme. It is included here for the sake of providing a broad discussion of all aspects of quantitative assessment of condition and likely performance in the context of flood defence asset management.

#### 6.4.1 Culverts and trash screens

Culverts act to ensure the conveyance of water rather than to provide an impermeable barrier against rising water levels. They can be found in both urban and rural locations.
though their use in heavily urbanised locales is probably more widespread. Culverts come in a range of shapes and materials though concrete and masonry culverts are the most common in the context of this work. No further description of the use and design of culverts will be given here. For more information see the latest Culvert Design and Operation Guide (CDOG) (CIRIA 2010). Figure 6.2 shows an image of a retired culvert and trash screen for illustrative purposes.

![Abandoned culvert and trash screen](image)

**Figure 6.2. Abandoned culvert and trash screen – Taken at Colwick Country Park, Nottingham**

Since channel conveyance is the primary function of a culvert, blockage due to the build up of debris within the culvert is the main performance issue. Trash screens can be installed at the upstream end of a culvert to prevent debris entering the culvert and causing a blockage which will be difficult to clear due to the confined space within the culvert. Trash screens become blocked with debris over time but can be easily cleared by operatives.

For trash screens, continuous monitoring rather than quantitative assessment is the main area of potential benefit. Debris build-up at trash screens can occur rapidly during extreme events reducing channel conveyance and raising upstream water levels. Continuous monitoring with fixed cameras as utilised in a recent EA trial (see appendix D) enables remedial action to be taken before significant blockages occur and reduces the need to inspect trash screens that are not suffering from blockage.

Where the internal state of the culvert itself requires assessment there are a number of potential options that could be employed to reduce the difficulties in access and visibility. Larger culverts can be inspected visually by inspection staff but it is likely that staff will need confined spaces training and safety equipment. However, many culverts are too small for inspection by an operative. Experience from the utility industries highlights two options for internal monitoring of culverts in these circumstances:

- Borescopes can be used to traverse short culverts and provide the inspector with a view of the internal conditions of the culvert. Any deterioration in the culvert surface can be established and the presence of debris build up can be identified.
• MLS can be used to obtain an accurate assessment of the internal topography of the culvert. A small remote drone can be used to traverse the culvert with a laser scanner attached.

• Robotic vehicles mounted with cameras and lighting can be used to acquire photography and/or video from within the culvert in a similar way to the sewer robots utilised by water utility companies.

Another project within the infrastructure theme of FRMRC2 (Work Package 4.1) is explicitly focussed on the analysis of debris build up at culverts and trash screens. This work is being undertaken by colleagues from the University of Nottingham and Herriot-Watt University. It discusses the issue in far greater depth than can be provided here and the reader is urged to consult recent and upcoming publications from this work for further information in respect of this type of asset.

6.4.2 Groynes

Similarly to culverts and trash screens, groynes are not a raised linear defence like the other asset types described thus far. Their role is to ensure that beach profiles are maintained and that there is no significant loss of beach material through natural drift and beach erosion. This is significant from a flood defence perspective since a loss of beach levels will increase flood and erosion risk by causing high wave and by leading to toe scour at sea defences such as walls or sloped revetments.

Groynes are often timber structures and will require regular maintenance and replacement due to the harsh environmental conditions in which they operate. Loss of timber boards is a common occurrence. Quantitative assessment is limited in its usefulness for monitoring groynes. Aerial remote measurement is only of use from an oblique perspective due to the slender cross-section of the asset. Oblique aerial photography will be able to identify any loss of material but commissioning an aerial survey for just this purpose would be excessive. Where aerial surveys of beach and shorelines are being carried out for other purposes then groyne monitoring could provide a useful additional benefit.

Ground based photography would be a sufficient method for quantifying the condition of groynes and repeated photography would be capable of detecting the rate of material loss over time.

6.4.3 Outfalls

Outfalls are another point structure. They are responsible for drainage of rainfall from the source into a channel or sea. They utilise a range of valve types to ensure that high water levels in the pathway do not flow back into the source and lead to potential flooding. Methods for performance based visual inspection of outfall type structures was discussed in previous work done in the initial phase of FRMRC (Long et al, 2006).

The outfall structure consists of a pipe covered by a valve which is embedded within another structure such as a vertical wall or its own apron (often constructed in concrete or masonry). Quantitative assessment of the actual outfall structure could utilise the various methods outlined for vertical walls for assessing the condition of the apron. The valve is the element of the outfall that is most critical to its performance. Quantitative assessment
by remote measurement or detailed inspection is not likely to be of great use in monitoring the valve’s condition. However, regular photography may be of some use in detecting change such as increased corrosion or movement of the valve.

Failure or blockage of the valve will reduce drainage and can lead to flooding during extreme or extended pluvial events. This is similar to the blockage of culverts or trash screens. As with those, continuous monitoring is therefore the option most likely to provide greatest benefits in terms of monitoring outfalls. Fixed cameras could be used to detect failure of the outfall valve in a similar way to the trash screen cameras described in section 6.4.1 and appendix D. Sensors could also be installed to check that the valve is opening and closing correctly.

### 6.4.4 Gabions and reno mattresses

To a large extent, gabions were covered in the discussion of gravity walls and sloped revetments as they are a potential construction material for both types of asset. Reno mattresses are similar in that they consist of a steel wire frame filled with loose rock and stone. Where they differ is that they are not a regular cuboid frame but are an irregular shape that is fitted to the terrain and filled in-situ. Figure 6.3 shows both gabions and reno-mattresses. It can be seen that reno-mattresses share similarities with revetments in that they can be used to protect a slope from erosion.

The irregular surface of gabions and reno-mattresses makes it difficult to quantitatively assess in the same way as concrete, masonry or steel structures. For gabions, the placement and position of each individual gabion basket can be monitored to ensure that the composite structure formed from them is not moving. Gaps between baskets can be measured and/or photographed to detect signs of deterioration. Reno-mattresses are more difficult to measure. Reference points could be marked onto the surface of a reno-mattress (e.g. with paint) to detect any movement or loss of fill material over time.

![Figure 6.3. Left - Reno-Mattress. Right – Gabion Wall](image)

Though rock-filled gabion baskets are the norm, it is not always the case. Figure 6.4 shows some sand-filled gabion baskets used as flood defence. These employ an impermeable outer bag or casing and would be suitable as a raised defence to hold back high water levels. For this type of gabion used as a temporary raised defence, quantification of damage and extent to the outer casing of each basket is essential. The close-up imagery shown on the right in Figure 6.4 demonstrates how damage to the outer casing could be quantified using photography as part of a detailed inspection.
Measurement tools could also be used to record the dimensions of any loss of casing for each basket where deemed significant.

![Example of sand filled gabion baskets – Newark, Notts. Close up showing contents on right](image)

**Figure 6.4. Example of sand filled gabion baskets – Newark, Notts. Close up showing contents on right**

### 6.4.5 Natural coastal defences

Natural defences such as beaches, dune systems, sea cliffs and salt marshes were not part of the initial scope of this project. However, during the research a number of methods identified were discovered to be already used for monitoring the condition of these natural coastal defences. A brief description of this is included in this section since it has relevance and illustrates ways in which the monitoring of raised linear defences could provide additional benefits. For example, data gathered by aerial remote measurement of coastal hard defences could also monitor beach profiles in front of the defence line. Beach levels have a critical role in the performance of the hard defences behind them as they control wave action and protect the toe of the structures.

A number of coastal groups exist comprised of maritime district authorities and representatives from others responsible for coastal defence. These groups perform a strategic role in planning and managing the state of coastal defence from flooding and erosion. Some of these groups were consulted during the initial research phase of the project and provided data and assistance to the project. These included aerial remote measurement datasets and elevation profiles for the south coast of the UK from the Channel Coastal Observatory (www.channelcoast.org; accessed May 2010).

Beach levels have been monitored usually Kinematic GPS and aerial LiDAR and photogrammetric surveys. All methods are capable of producing profiles of beach levels and detecting changes to beach levels over time. The Southern Coastal Group found Kinematic GPS to be the most effective method for repeated monitoring. It can be mounted on a mobile platform such as a quad bike for monitoring large areas relatively rapidly. There is also a programme, which has been in operation since 1980, of photographic and video monitoring for detecting change or deterioration of beaches used internationally. This uses 10-minute time exposure (Timex) images (Lippmann and Holman, 1999).

Salt marshes are suited to airborne remote measurement surveys and have been monitored by both LiDAR and photogrammetry. Both methods can detect loss of salt
marsh levels and extent. Both of these can have a significant impact on flood risk for the area. Terrestrial methods are less capable due to difficulties in accessing the salt marsh by foot or terrestrial vehicles.

Cliff erosion and retreat is a rapid and dynamic process in many areas of the UK. Continuous monitoring sensors such as accelerometers and inclinometers have been trialled and tested for monitoring this process and establishing the rate of deterioration.
7 Case studies and trials

During the research a number of trials were undertaken and data was collected from the EA and other sources. This data was analysed and used for a number of case studies. This chapter describes a number of these trials and case studies to back up key points made throughout the report and highlight the potential benefits, and limitations, of many of the methods that could be employed.

It is not practical to include all the analysis work and case studies within this chapter. Additional detail on those examples given here and further examples highly relevant to the project are provided in the appendices of this report (appendices A-F).

7.1 Computer based simulation of LiDAR

A significant constraint on the regular use of LiDAR for asset monitoring is the time, logistics and cost associated with performing aerial surveys. Though relatively low cost per square kilometre in comparison to ground-based surveying options, it is still an expensive process to carry out for regular asset monitoring as this is typically carried out annually or at greater frequency. Further research on the utility of high resolution LiDAR in this role is needed to determine its optimal use for flood defence monitoring. In particular, it is essential that aerial surveys are carried out to maximize the possibility of detecting faults in defence systems by selection of appropriate grid resolutions, point densities and site conditions.

It was determined that computer simulation of LiDAR surveying of embankments would be a potential method of investigating the influences of the quality of a LiDAR survey. This could enable flood defence system managers to identify appropriate LiDAR survey parameters to detect specific types and magnitudes of faults arising from surface deformations.

In order to simulate a LiDAR survey of an embankment, software (Embankment Simulator) was developed using VB.NET within Visual Studio (Figure 7.1). Embankment Simulator can create a full embankment with simulated LiDAR data and a failure with specific dimensions in four steps:

1. The first step is to create a data file based on 3D coordinates (Easting, Northing, Height) representing an edge or toe of either slope of the embankment. This file is then loaded into Embankment Simulator using the Read File option.
2. Within Embankment Creator the user then specifies the width and the height of other sides of the embankment. The full embankment, consisting of three polygons/sides (left slope, crest and right slope), is then created.
3. The third step is to simulate a LiDAR survey of the created embankment. This is done within the software by interpolating the height of the LiDAR points located within any of the three polygons using the closest four points of that polygon plus a random height (specified in the Interpolated Height ± box). The variability of the generated heights around the ‘true’ value represents the accuracy of the LiDAR survey. In the discussion below, this is referred to as ‘noise’ but in reality it depends of many factors including the vegetation on the ground, the quality of the scanner and the atmospheric conditions. Some of these are in the control of
the operator, others are not. The controllable factors can be defined for any survey and will affect its price.

4. The last step is to simulate a failure within the embankment. The initial version of the simulator allows the user to produce a rectangular failure in a random location within the left or the right slopes with a user specified resolution, e.g. 10cm.

After the embankment has been created, the user can press ‘Run Simulation’ button to produce a new set of LiDAR points which take into account the failure. The output files (one simulating the situation before failure and the other representing the situation after it) in LiDAR ASCII format can then be imported into ArcGIS or similar software for further analysis.

![Embankment Simulator software](image)

**Figure 7.1. Embankment Simulator software**

As an example, to produce a profile of one edge of a trial embankment ten points were measured in Google Earth. This data was then used in the Embankment Simulator to produce two sets of LiDAR files with 1.0m grid resolution. The first set of simulated LiDAR data was for the whole embankment without any failure with noise of 0.10m and the second set used similar parameters but included a failure of 5x6m with a depth of 1.0m. The failure was simulated similar to the one in Figure 7.2.
The LiDAR ASCII file can be imported within ArcGIS packages for surface analysis and visualisation purposes. Within ArcGIS, the differences between the two sets of the LiDAR data can be calculated. For the simulation carried out for the 1.0m grid resolution with failure of 5x6m with a depth of 1.0m, the differences between the two sets are illustrated in Figure 7.3.

From Figure 7.3 right, it can be seen there is quite a lot of noise between the simulated LiDAR data sets, however, there is a small group of red pixels of height -0.92m detected in the failure location.

Although the failure of 1.0m can be detected in a simulated LiDAR with grid resolution of 1.0m (Figure 7.4 -bottom right-), it is difficult to extract precise dimensions of such a failure. Therefore, another simulation LiDAR data was generated for a particular part surrounding the failure with grid resolution of 0.125m (Figure 7.4 -top and left-).
Figure 7.4. Simulated LiDAR data with grid resolution of 0.125m and failure of 1.0m (top and left) and with grid resolution of 1.0m (bottom right)

A failure depth of 0.2m with dimensions of 5x6m was also simulated and - similar to the previous simulation – two simulated LiDAR datasets were generated with grid resolution of 0.25m and noise of 0.1m. The differences between the simulated two surfaces as well as between the slope of these surfaces were calculated in ArcGIS and illustrated in Figure 7.5.

Figure 7.5: Difference between simulated LiDAR datasets with 0.25m grid resolution and noise 0.1m of surfaces (left) and slopes (right)

Although there are a few red pixels in Figure 7.5 (left) on the location of the failure, the slope difference (Figure 7.5 right) does not show the failure. This is due to the large magnitude of noise within the LiDAR simulated data. This would indicate that a LiDAR survey with this magnitude of accuracy would not be suitable for identification of features of the size of that considered in the simulation.

Another simulation was carried out with LiDAR noise of 0.05m and the differences between the simulated two surfaces as well as between the slope of these surfaces was calculated in ArcGIS and illustrated in Figure 7.6.

Comparing Figure 7.5 left with Figure 7.6 left, there are more red pixels in Figure 7.6 left on the failure location due to the reduction of the simulated noise. Also, the slope
difference shows the failure in Figure 7.6 middle and it becomes more obvious after applying a maximum 5x5 filter to the slope. This would indicate that the improvement in accuracy of the survey has made it possible to identify the feature. Whether it is possible to achieve this new accuracy in reality will depend on the values of the non-controllable factors described above and the amount of money the manager is prepared to spend to specify the controllable factors.

Figure 7.6: Difference between simulated LiDAR datasets with 0.25m grid resolution and noise 0.05m of surfaces (left), slopes (middle) and filtered slopes (right)

A number of other simulations were carried out for a range of different embankments and surface deformations to further examine the effects of data resolution and noise levels on the DSM produced. Some enhancements to the simulation were also introduced so that a wider range of fault types could be simulated and ground levels could differ on the inner and outer face of the embankment. Further details and results from the simulation are given in appendix A.

The simulations have shown that the accuracy requirements of LiDAR, or any DSM measurement technique, can be critical in assisting the identification of potential failures. The simulation has shown to be a useful tool in helping to establish accuracy requirements. This work could be further expanded to produce a more flexible and robust tool for planning LiDAR surveys by asset managers but this is outside the scope of this project.

7.2 Analysis of airborne remote measurement data

This section will examine a range of LiDAR DSM datasets made available to the project by the Geomatics group (a major source of aerial survey data for the EA). Examples of DSMs at varying levels of detail will be examined and discussed in the following subsections.

7.2.1 Case Study 1 – Low resolution datasets

Figure 7.7 shows low resolution LiDAR data with a grid resolution of 2m. The area shown is in the vicinity of West Stockwith and shows the confluence of the river Trent and the river Idle. The Trent at this point is tidal and is a wide channel (approx. 30m). The 2m DSM shows little specific detail though the outline of embankments along the sides of the two fluvial channels is clearly defined.
The area and its defences are well known as they were used as part of the asset inspector’s training course for a number of years. There is a range of defence types including vertical walls that cannot be identified in the 2m DSM around the confluence of the two channels. There is an apparent ‘break’ in the defence line at this point which is actually defended by a slender gravity wall and this asset is missing from the 2m DSM. This confirms results from simulation and calculation that low resolution LiDAR will not identify such asset types or small surface features. It is clear that any minor surface deformations are therefore unlikely to be detectable at this level of resolution.

![Figure 7.7. LiDAR DSM 2m grid size, West Stockwith, Notts., March 1999](image)

This is confirmed from the analysis and comparison of LiDAR data for the Thames region shown in appendix E.

### 7.2.2 Case Study 2 – Intermediate resolution datasets

Intermediate resolution data was obtained in the area of the town of Carlisle in Cumbria. The full extent of the DSM dataset obtained is shown in Error! Reference source not found.. The DSM has a grid resolution of 0.5m and the survey was carried out in 2005, shortly after the major flooding event that occurred in the local area.

Compared to the low resolution DSM shown in section 7.2.1 it is clear that there is a large increase in the detail at this resolution. Figure 7.9 illustrates this using an oblique viewpoint of a portion of the dataset. Hedgerows, trees and the embankment supporting the local railtrack can be clearly identified on the left of the image. The topography of the terrain is well defined and large raised features can be identified. The rail embankment was measured in ArcGIS and is 3-4m above ground level.

Although visible, smaller surface features such as the hedgerows and trees lack detail and it is clear that small surface features and deformations such as those associated with the
asset condition and potential failure would not be easily detected at this level of resolution. This is confirmed by the simulation discussed earlier in this chapter.

Figure 7.8. LiDAR DSM 0.5m grid size, Carlisle, Cumbria, 4th April 2005 (three months after major flooding event)

Figure 7.10 shows a close-up of a small portion of the dataset and comparable oblique aerial photography (taken from maps.bing.com; accessed April 2009). A large lowered section can be seen in both images and the height difference was calculated to be approximately 3m from the LiDAR DSM. Although evident in the DSM, this large change in elevation is not clearly defined and it is likely that similar but smaller features such as those indicative of a circular slip in an embankment slope would not be easily detected as this resolution.

Figure 7.9. Oblique viewpoint of LiDAR data. Rail embankment clearly visible on LiDAR along with hedgerows and solo tree at point x. Embankment height between 3-4m
7.2.3  **Case Study 3 – High resolution datasets**

Research and results from the simulation indicated that high resolution LiDAR DSM data would be necessary for asset monitoring. A grid resolution of 0.25m or less is indicated but limited actual data at this resolution was available. A trial of high resolution LiDAR data was identified and acquired for analysis.

The LiDAR area available for analysis is for Wisbech in Cambridgeshire (Figure 7.11). There are two datasets available, one with 1m grid resolution and another one with 0.15m grid resolution.

The 0.15m grid resolution available data overlapped with the 1m grid data in a small area. Within this overlapped area, a wall was selected in area A (Figure 7.11) for analysis purpose. Using ArcGIS, the difference between the two LiDAR sets was calculated as well as the difference between their slopes (Figure 7.12).

The difference of the height between the two LiDAR sets is about 0.05m (some differences are about 0.10m) in most of the green area (Figure 7.12 left). The difference in the height on the wall (Figure 7.12 left A) is about 1.0m (cyan colour). This difference has been amplified using the slope difference in Figure 7.12 right. There are large differences (up to 14m) on the buildings and trees areas.
7.3 Kinematic GPS for assessing asset geometry

As described in chapter 3, assessment of crest height is an important aspect of monitoring flood defences. Kinematic GPS was identified as being one possible method and trials were therefore carried out to evaluate it.

7.3.1 Trial 1 – Wheel mounted GPS

A trial was carried on an embankment at Silverdale near Nottingham utilising the Leica 1200 GPS receiver, working with the Leica SmartNet (RTK network). Since the data collection requires continuous positions to be recorded whilst moving along the top of the embankment, the 1200 receiver was fixed on a surveying wheel. Using this wheel, the tilt of the GPS antenna needs to be taken into account and correction should be applied to overcome this tilt.
A digital compass with an integration system (includes GPS and camera) was utilised for the data collection (Figure 7.13). The data collection started at the north of the embankment (Start Point - Figure 7.14 left) the route went along the top towards the south (End Point) with total length of 875m. On the way back, the two sides of the embankment were partially surveyed as well as about 100m of the top (Figure 7.14 left).

Figure 7.14 shows the full Silverdale Embankment positioned by RTK points (left) and from aerial photograph obtained from Google Earth (right).
From Figure 7.14, the lowest GPS height was found to be equal to 75.08m. However, the height of the embankment with regards to its sides varies from 0.6m in the east side in the middle of the embankment to 2.3m on the west side near the start point of the embankment. To illustrate the changes in the height of the top of the embankment, a profile was drawn as shown in Figure 7.15. As can be seen from Figure 7.14 right, area A is close to trees which make it very difficult to achieve centimetre level RTK position. Also, a discontinuity of the position is clearly shown in Figure 7.14 left and in the profile (Figure 7.15).

The magenta and the red colours on the profile (Figure 7.15) are the backward data on the top of the embankment. These areas were enlarged in Figure 7.16 (before area A -up, and after area A -down) for illustration purposes. The differences in the height in these profiles could be due to several reasons including different tracks taken on the crest by
the surveyor and GPS antenna tilt. Since it is very difficult to return along exactly the same route, differences in the height are expected due to the different location. For example, the maximum difference in the height was found to be 0.13m on the station 629.40m (RTK points: RTK0954 forward data and RTK1487 backward data) (Figure 7.16 down). The distance between these RTK points was 0.85m. So, this is one of the reasons for this difference. As mentioned earlier, the typical RTK accuracy is 1cm E, N and 2cm in height. Furthermore, the tilt of the GPS antenna can affect the height. The average effect of the tilt angles over the 360 points (which were collected on the start of the embankment) was 0.014m with maximum error of 0.065m.

A larger version of the profile can be found in appendix F.

Figure 7.16. Profiles of the forward and backward survey of the top of Silverdale Embankment before area A (up) and after area A (down)
7.3.2 Trial 2 - Backpack mounted GPS

Another set of RTK GPS data was collected on the top of Silverdale embankment. The technique for the data collection was similar to that in Silverdale Trial 1. However, the GPS receiver and the antenna were fitted in a bag on a colleague’s back (Figure 7.17). The data collection was performed at a slow but steady walking pace. The height of the GPS antenna was recorded and the data collection was performed forwards (from a start point to the end of the Silverdale embankment – Figure 7.14) and backwards (return to the start point).

Figure 7.17. Collection of GPS RTK data on Silverdale embankment using backpack

In order to illustrate the changes in the height of the top of the embankment, a profile was drawn as shown in Figure 7.18. Similar to Silverdale Trial 1, area A, which is close to trees, makes it very difficult to achieve centimetre level RTK position and a discontinuity of the position is clearly shown in the profile.

Figure 7.18: Profile of the top of Silverdale Embankment in trial 2 (note: different scale for the horizontal and the vertical axes)

Similar to Trial 1, area A a gap was found around the distance 600m. From Figure 7.18, there is a good matching between the forward and backward heights in the area between 0
and 100m and the area after 240 to the end of the embankment. However, there is an area between 100 and 240 with an average difference between the forward and backward height on 0.14m with a maximum difference of 0.24m. The difference could arise from the same sources as those that were discussed in Trial 1. In addition, there would be an additional error from the up and down motion of the surveyor’s gait.

As mentioned in Trial 1, one of the reasons of the differences is the difference in walking path taken. To investigate, this area between 100 and 240 was plotted and is shown in Figure 7.19.

Figure 7.19. Plan plot of Silverdale Trial 2 of area between 100m and 240m

Figure 7.19 shows that there was a difference between the forwards and backwards walking paths of up to 0.80m. This could be the main source of the difference in height.

In addition to the previous comparison, it is worth comparing between the profiles of the two trials (Trial 1 and Trial 2). In Figure 7.20 -which shows the profiles from different trials- the forward profiles of trial 1 and trial 2 are quite closely matched in most places. However, the reasonably constant difference in height in the area between 100 and 240m between the forward height of trial 1 and the backward height of trial 2 confirms the effect of the different route. If it was due to the tilt of the antenna pole it might expect to be more variable.

Figure 7.20: Profile of the top of Silverdale Embankment in trial 1 (T1 forward and backward) and trial 2 (T2 forward and backward) (note: different scale for the horizontal and the vertical axes)

Based on the above analysis, if GPS RTK data were collected on well defined points, the backpack mounted version should be capable of producing profiles of about 10cm height accuracy. This level of accuracy should be more than sufficient for the needs of crest
profiling (see table 2) but the level of precision should be noted and considered where crest height measured is close to the level required by the defence’s SoP.

7.3.3 **Trial 3 – Backpack mounted GPS profiling poor condition coastal embankment**

It was decided to perform a repeated trial of the backpack mounted RTK GPS system for an embankment in very different condition to the Silverdale embankment. A coastal embankment in poor condition at Hayling Island near Portsmouth was selected as it offered the opportunity to test the method on an embankment with a very narrow and irregular crest. Figure 7.21 shows the area surveyed overlaid onto a LiDAR DSM. The embankment was assessed as being condition grade 4 (poor) at its last visual inspection. The defence is no longer managed by the EA and has been retired as part of a strategic realignment of flood risk for the local area.

There were significant low points identified and damage and signs of deterioration to both the inner and outer slopes. Recent remedial work had been undertaken to raise the crest level in an area a few metres south of the start point of the survey.

![Figure 7.21. Extent and reference points for trial 3 superimposed on LiDAR DSM data](image-url)
As shown in Figure 7.21, the survey path started around the midpoint of the area to be profiled due to access limitations. The embankment crest was surveyed in a northerly direction and then a return pass was made to the start point. This was then repeated for the southern leg of the surveyed area. Approximately 800m of crest were profiled. This took approximately 1 hour to complete.

The irregularities of the crest made it more difficult to ensure that the lowest point was profiled on each pass of the route in comparison to the Silverdale trial but the results obtained correlated well with expectations and existing data for the area.

![Crest profile for trial 3 (Hayling Island embankment)](image)

**Figure 7.22. Crest profile for trial 3 (Hayling Island embankment)**

Key statistics acquired from the survey are as follows:
- Minimum crest height identified = 2.62m
- Maximum crest height identified = 3.22m
- Maximum difference between outward and return routes = 0.10m
- Elevation precision obtained according to the GPS receiver diagnostics
  - Minimum = 0.001m
  - Max. = 0.042m
  - Ave. = 0.013m

It should also be noted that the crest height required for the SoP that the embankment offered prior to its retirement is 3m. It is clear that a significant section of the area surveyed was below the SoP. An enlarged version of the crest profile for this trial can be found in appendix F.

### 7.3.4 Fault profiling with RTK GPS

RTK GPS data was collected on a small part of an embankment at Shelford near Nottingham containing a circular slip using a pole mounted receiver for increased accuracy. From these points, it is possible to create a mesh and to do some calculation. For example, it is possible to measure the dimensions of the failure (These were: 5.77mx1.85m and 0.42m depth).
In addition to the RTK GPS positions, three geo-referenced pictures were taken using the integrated system described previously. Another three images from approximately the same location were also taken using an SLR digital camera (Nikon D300). The geo-referenced pictures and their embedded information as well as the SLR pictures are illustrated in Figure 7.24.

As can be seen from Figure 7.24, the SLR cameras provide high resolution imagery and would have the potential for terrestrial photogrammetry if measurements were required.

The trials described here demonstrate that RTK GPS is a suitable technology for monitoring the crest levels of stretches of embankment to an accuracy of a few centimetres. They also demonstrate that the method is suitable for single person operation and that it is therefore a practical alternative to the methods currently in use.
7.4 Inferring geotechnical conditions from aerial remote sensed data

Contact was established with a geotechnical engineer, Shaun Wersching, from the Halcrow Group through our industrial collaborators. He routinely employs LiDAR, aerial photography and mapping data to assess potential geotechnical issues in order to intelligently target geotechnical investigations.

This method does not necessarily require high resolution DSM data as it is focused at the reach or sub-reach spatial level. It requires general geotechnical knowledge and some knowledge of local geotechnical conditions. It does not provide detailed quantitative data but it is capable of identifying potential sub-surface features without the need for expensive and time consuming geophysical monitoring or invasive geotechnical surveys. It relies on LiDAR’s ability to penetrate vegetation to a limited degree allowing features obscured by crops and grass cover to be identified. Combining this data with both recent and historical mapping data enables the inspector/consultant to identify subsurface features such as old drainage channels, historical navigation routes, presence of old works or buildings, etc. The presence of subsurface features can then be used to predict likely geotechnical conditions and potential asset performance issues, potentially triggering detailed inspection, specific monitoring regimes or even intervention.

An example of this process is shown in Figure 7.26 and Figure 7.26. Seepage had been identified to be occurring to embankments located to the east of the village of Billinghay in Lincolnshire. shows a combination of LiDAR DSM and OS Map data for the area. The village of Billinghay is on high ground (represented by the orange) surrounded by much lower ground (represented by blue). The topography in ancient times would have seen a small settlement on a gravel mound surrounded by marsh which was flooded in winter. After the draining of the fens in the late 18th century the area became rich agricultural land as it is today.

Analysis of the combined DSM and map data highlighted a raised (yellow) area to the east of the village. The shape and position of this section led to the deduction that it represented the presence of a rodden. (A rodden is a dried, raised remains of a watercourse such as a river or tidal-creek common in the Lincolnshire and East Anglian fens. It consists of sand and silt resting on the underlying peat and clay and raised above the surrounding ground levels. It is common for towns and villages to be built on roddens.)

The increased permeability of the soils in a rodden led to the conclusion that this was the most likely cause of the seepage. The extent of seepage was then identified and was found to match very closely to the yellow raised area to the East of the village. This allowed the detailed geotechnical investigations and remedial work to be focussed on the specific area of need and reduced the need for invasive and wasteful investigations outside the affected area.

This is just one of numerous examples provided and illustrates the potential of the method. Though it does not provide quantitative data in the true sense, it enables subsurface features to be predicted and can be used to intelligently target detailed investigation work. It many instances it can match or even outperform GPR based surveys which can often be inconclusive in their results.
Figure 7.25. Integration of LiDAR DSM with OS Mapping data for area near Billinghay, Lincolnshire © Crown Copyright, Ordnance Survey. All rights reserved.

Figure 7.26. Close up view for area affected by seepage problems (corresponds with yellow area east of Billinghay) © Crown Copyright, Ordnance Survey. All rights reserved.
8 Conclusions

This chapter is intended as a brief summary to the report and highlights important findings. It should be read in conjunction with the summary table. It does not specify how these may be utilised in the context of flood defence management as this is the remit of the final chapter of the report. With respect to the stated aims and objectives of this work, some general conclusions in terms of quantitative assessment methods are drawn. These are followed by findings relevant to the specific types of quantitative assessment methods used throughout the main body of the report. Areas where further research may be needed are then listed and the chapter concludes with a brief discussion of potential future developments for asset monitoring and how these may impact flood risk management. Given in appendix G are the following tables providing a summary of potential technologies and methodologies for flood defence asset monitoring: system level surveys; detailed inspection remote monitoring; indicator/asset type summary; and a technology summary.

8.1 Quantitative assessment and performance based inspection

The following general conclusions are in regard to quantitative assessment of flood defence assets:

- Quantitative measures of key parameters are an important element of asset performance models. All performance models require quantitative values for performance parameters.
- Current qualitative assessment methods (i.e. visual inspection) mitigate this issue by making estimates of performance parameters based on subjective condition measures. For example, condition grade for bank slopes can be used to estimate values for the quality of grass cover.
- Accurate assessment of asset geometry is a key input to many of the available performance models. Subjective judgment of geometry is not sufficient for accurate assessment of performance.
- Crest height in particular, is a critical measure of likely asset performance for raised defences. It represents the asset’s SoP and cannot be accurately assessed through a solely visual inspection.
- Changes to asset geometry (e.g. settlement, heaving, slumping) are indicators of deterioration and potential failure. Quantitative assessment of change can be useful in identifying dynamic failure processes and their progression.
- Geotechnical parameters related to subsurface features are extensively used in asset performance models. These are difficult to assess quantitatively through non-invasive methods.
- It is clear that accurate measures of key performance parameters would be a valuable input to assessing the condition and likely performance of flood defence assets. Both absolute values and measures of change to parameters can be used to improve the assessment.

8.2 Remote measurement

In terms of the potential for remote measurement in asset monitoring, a range of methods was assessed to varying degrees of detail. LiDAR was the primary method examined due to its widespread use in topographical surveying and its increasing use in infrastructure monitoring. Aerial photogrammetric methods were also examined in depth due to their
ability to produce high-resolution imagery of surface condition of large areas in a single flight. Both radar- and sonar-based methods were also examined to a lesser degree as they provide unique opportunities not afforded by other methods.

Conclusions regarding the use of LiDAR for asset monitoring applications are as follows:

- LiDAR can assess asset surface geometry to a high level of accuracy suitable for use in assessing condition and likely performance.
- LiDAR is highly effective at assessing crest levels but manual processing of data may be necessary to generate a crest profile. This is especially true where other structures or features are in close proximity to the asset crest.
- The distance from the laser scanner to the target is a major source of error in LiDAR surveys - accuracy decreases with range. High altitude aerial surveys may therefore be of limited value for monitoring flood defences to a high level of accuracy.
- Raw point cloud data generated by LiDAR surveys is processed to generate a DSM. The procedure used to create the Digital Surface Model (DSM) involves the creation of a grid of points containing positional data. Each grid square is created by averaging the point cloud data (longitude, latitude and elevation) within that square. This inevitably reduces the terrain detail.
- Generally, high resolution DSM data (<1m grid size) is necessary for assessing asset geometry. Lower resolution data can be useful in detecting large-scale trends and surface features but will lack detail and accuracy for individual assets.
- Heuristically, in order to have confidence that a features will be detected the resolution required should be at most half the size of the feature. For example, to identify surface features such as slumping or heave with a dimension of 1m * 1m would require a DSM grid size of 0.5m or less.
- Analysis of existing LiDAR datasets combined with results from computer simulation of LiDAR tends to indicate that a DSM resolution of 0.25m or less will be required to detect small surface deformations related to asset failure modes.
- Aerial LiDAR surveys can be affected by atmospheric conditions and features obscuring the asset surface (e.g. trees or shrubs). The presence of other surface structures close to the asset may produce inaccurate positional results. Generally, this is not a major issue in a flood defence context as assets are kept free from obstructions. However, overhanging trees could be an issue in some areas.
- Low altitude aerial surveys are typically employed in asset monitoring applications. Helicopter mounted systems such as FLI-MAP have been used in a number of similar surveys in the UK (e.g. TE2100, Network Rail mapping of east and west coast main lines) and are particularly suited to mapping narrow corridors such as highways, railways, fluvial channels or coastlines.
- MLS systems have the potential for greater accuracy over aerial surveys. However, coverage is greatly reduced and access to the entire defence line is needed. Access could be a particular issue for flood defences since, unlike rail or highway infrastructure, there is no existing pathway for the mobile vehicle to utilise.
- TLS systems can produce a detailed assessment of surface geometry for individual assets but are not practical in monitoring large areas.
- Both MLS and TLS systems do not require the raw point cloud data to be converted to a DSM format and therefore do not suffer from the loss of detail associated with the processing of the DSM. They may therefore be well suited to monitoring small scale change and surface deformations associated with failure.
• Smaller assets presenting a slender cross-section such as vertical walls would need sufficiently low grid size for accurate assessment of crest height. However, their hard, reflective surface should provide a more precise assessment of elevation in comparison to a grass-covered embankment. This increased precision would also apply to most revetments materials. On the other hand, the nature of these asset types means that their structural tolerances are typically smaller, increasing the requirements for precision and accuracy of monitoring.

• Standard LiDAR is reflected by water and therefore cannot assessing asset geometry below the current water level.

• LiDAR using a blue laser can penetrate water but is currently too expensive for practical use in a flood defence monitoring context.

• Computer simulation of LiDAR surveys has been shown to be an effective method for assessing the quality of data produced and the likelihood of detecting faults. This work could be expanded upon to provide a tool for asset managers to determine the appropriate type of LiDAR survey needed for their purposes.

Aerial photogrammetry can produce similar levels of positional accuracy to LiDAR in good conditions and offers additional benefits. Key points relating to the use of photogrammetry in asset monitoring are:

• Like LiDAR, aerial photogrammetry would also need to be of sufficient resolution to identify performance features. 5-10cm/pixel should be an appropriate resolution for asset monitoring purposes.

• Photogrammetry produces a visual record of surface condition and can highlight features not represented by a change in positional values. This is a significant advantage over LiDAR which only produces positional data. For example, bare patches of earth on an embankment would be visible on aerial photographs but may not be identifiable on a LiDAR DSM.

• Photogrammetry requires a clear view of asset surface. Poor atmospheric conditions, such as cloud cover, limit its use.

• Photogrammetry can require additional post-processing compared to that required by LiDAR.

• Advances in camera technology mean that photogrammetry can produce similar levels of accuracy and resolution at much greater altitude than airborne LiDAR. It therefore has increased coverage and can produce results over a wider area in a single pass. It would therefore be a more efficient method for aerial surveying over large areas.

• Near IR photogrammetry highlights the presence of vegetation and has been used in agricultural monitoring to identify crop type and growth. This makes it of potential use in monitoring the state of vegetation on and around flood defences, e.g. the condition of grass cover on embankments and the presence of water-loving vegetation which could indicate signs of seepage.

• In some instances, analytical photogrammetry can exceed the accuracy of LiDAR. Slender features such as vertical walls are a particular example of relevance to this work.

• Oblique aerial photogrammetry can be useful in assessing the condition of perpendicular elements such as the inner and outer faces of vertical walls.

Radar-based remote measurement is not capable of providing absolute positional values unless it is integrated with other positional datasets (e.g. data from GPS stations).
However, it is capable of detecting change between two radar datasets at high level of accuracy. It is not affected by cloud cover and is therefore suited to space-based or high-altitude surveying. It can therefore provide very high coverage and is ideal for monitoring terrain over very large areas. It is suited to detecting large-scale land movements associated with mining subsidence or natural processes. It could therefore be useful at the regional level and as part of long-term flood risk planning.

Sonar-based systems such as wide-swath bathymetry can be used to assess underwater conditions. Such systems have been used in assessing condition of port structures and would be capable of detecting toe scour and slipping where asset are under constant hydraulic loading. The EA currently employs sonar systems for fisheries monitoring and this could be adapted to for flood defence monitoring where conditions warrant its use.

8.3 Continuous Monitoring

Continuous monitoring covers the use of sensing equipment that is placed on, within or nearby flood defence assets and can be used to measure asset condition outside the regular inspection regime. It includes electrical and mechanical sensors such as motion detectors, moisture sensors, measuring gauges and fixed cameras. Many of these types of monitoring device are currently used in the management of dams and reservoirs due to the extreme consequence of their failure. The installation of subsurface sensing equipment is invasive and may be more suited to new defences during the construction phase. However, the potential benefits of detecting subsurface changes may be sufficient to warrant their inclusion in existing defences of particular criticality. Other findings in regard to continuous monitoring are:

- The ability to maintain a record of performance indicators at regular intervals or continuously is the key benefit of this approach. It enables a record of condition under loading and during extreme hydraulic conditions to be collected. Since failure often occurs under extreme conditions and is not evident under normal loading this is a significant advantage offered.
- Collection and transmission of monitoring data is an issue. Telemetry or on-site data storage will be needed.
- Power use by electrical sensing equipment must be considered. Access to mains power is not possible in remote locations and may be impractical in urban or suburban locations. Low power equipment and self sufficient power sources (e.g. solar, wind) could be necessary.
- Alarm-based systems (when a sensor detects value below a specified threshold, an alarm is triggered) may be an alternative option to avoid data storage and power use issues. There would obviously still need to be a method for transmitting the alarm to asset managers.
- The location and distribution of sensors is a critical issue for continuous monitoring. Analysis of likely asset performance and potential areas and types of failure would be necessary prior to installation of equipment.
- Sensor lifespan and robustness is another major concern. Flood defence assets generally have long lifespans, greatly in excess of the sensor equipment. Sensors must be capable of withstanding the local environmental conditions and hydraulic loads.
- Motion sensors (surface mounted or internal) such as accelerometers are capable of detecting asset movements associated with failure. However, regular calibration may be necessary for positional accuracy as these types of sensor are prone to drift.
over time. For relative rather than absolute assessment of movement this should not be a major concern. Inclinometers can be used to detect any change in slope or wall angle that could indicate asset deterioration or impending failure.

- Subsurface moisture sensors could provide a mechanism for detecting internal seepage or increased saturation. This is not easily detectable through other approaches but their installation will be invasive and only suitable for critical and new build assets.
- Fixed cameras have been utilised in trash screen monitoring by the EA. This demonstrated a method by which they can be effectively used in monitoring flood defence assets. Quantitative assessment of surface geometry within view of the camera would be possible.

8.4 Detailed asset inspection

In terms of quantitative monitoring at the asset level there are several potential options, many of which are specific to a particular type of asset. The methods and techniques that can be applied can be categorised into two broad categories: surveying and NDT. NDT methods tend to be asset specific and surveying-based methods tend to be more generally applicable. The complexity and resource requirements range from simple tools that could be employed within the standard visual inspection regime to complex methods requiring specialist equipment and training (and possibly best suited to use by expert consultants). Discussion of how detailed asset inspection could fit into overall flood defence asset management is given in chapter 9.

The main points to conclude in relation to surveying based methods for detailed asset inspection are:

- Basic measurement and levelling tools can be used to quantify performance features such as rutting, cracking, slumping and crest and slope angle to a sufficient degree of accuracy with minimal training and extra resource requirements
- Markers to be used for measuring any change to asset surface can be placed directly onto the asset surface. For example, crack length could be marked on the face of a wall to identify any increase in cracking in subsequent inspections.
- Tell-tales and simple gauges can also be placed onto the asset surface for monitoring changes over time.
- Kinematic GPS has been shown to be a useful method for accurate assessment of asset geometry (and in particular crest height) for single assets or small groups of assets. An accuracy of around 10cm in elevation can be obtained using a simple backpack-mounted system. This enables profiles to be collected at walking pace rather than the much slower pace associated with traditional ground-based surveying methods. It also can be carried out with minimal training and by a single inspector (assuming there is mobile phone reception available to connect to the GPS reference network, otherwise an extra receiver and staff member would be needed)
- Kinematic GPS could be mounted on ground vehicles to rapidly collect asset geometry data to a high level of accuracy. This approach has been adopted in beach monitoring programmes on the south coast of the UK. For embankments subject to regular grass mowing, the mounting of kinematic GPS on mowing equipment which fully traverses the embankment would enable collection of asset profiles for the entire asset. This would offer significant efficiency savings as asset
geometry data could be collected without the need for any additional time spent or resource needs.

- Photography of key performance features can be used to quantify and record asset condition. Current visual inspection methods include the scope for asset photography and its inclusion in the NFCDD. However, this process is not formally defined and is currently at the discretion of an individual inspector. Increased standardisation of its use and geo-referencing will increase the utility of photography taken.
- Fixed-point photography using a tripod can be used to acquire quantitative data on geometry or performance features if supplemented with some simple measurements (e.g. distance from fixed point to reference points on asset).

Findings in relation to NDT based methods for detailed asset inspection are:

- Geophysical methods show most promise in flood defence monitoring. They enable subsurface monitoring non-invasively and to a depth suitable for flood defence monitoring. They have the potential to allow the detection of voids, foreign objects and differences in soil conditions within an entire asset. Geophysical equipment does not necessarily require expert operation and Geophysical surveys could be carried out by asset inspection staff with some training.
- Geophysical monitoring equipment is currently expensive and the results require processing and interpretation by an expert. Standard GPR methods are not suited to heavy, clayey soils (such as those commonly used in flood defence foundations and earth embankments) which can limit penetrative capacity. However, the EU funded IMPACT project (IMPACT Geogroup, 2008) has highlighted Geophysical based methods more suited to such conditions – Geoelectric monitoring.
- Geophysical methods can produce false-positives. They should not be relied upon as the sole source of data and is best used to confirm or clarify results obtained from other sources. For example, signs of slumping or cracking in a slope could be investigated by a GPR survey of the local area. This could identify internal voiding as the cause of the surface deformations.
- ERT has been shown to be capable of detecting internal moisture levels in embankments and foundation soils. Excessive moisture levels, areas of saturation and rapid changes in moisture can all be responsible for deterioration and failure of flood defence assets. Being able to monitor internal moisture levels has the potential to be of major use to asset managers. However, research could not establish that the technique has been used successfully in a flood defence context and it is a slightly invasive procedure as it requires electrodes to be placed into the ground.
- Acoustic emission analysis is not currently sufficiently accurate and reliable a method for the monitoring of flood defence infrastructure.

8.5 Areas for further research

As with any broad ranging research project, there are always elements of the proposed work that cannot be fully explored due to temporal, budgetary or other constraints. This section lists areas where additional research or trials may be usefully undertaken to confirm or clarify or refine the findings stated. Examples where additional work may be warranted are:
• Kinematic GPS - Trialling the profiling of embankments using mowing vehicles and equipment as the surveying platform.
• LiDAR – Integrating subsets of raw point cloud data with DSM datasets. Where areas in DSM showing anomalies or uncertainty are identified it would be useful to be able to view the data in the raw point cloud for that area to identify small-scale deformations that may have been obscured in the DSM.
• Near IR Photogrammetry – Determining the capability for indentifying vegetation type from imagery is not new but it would be particularly useful to undertake trials specifically on vegetation types found on embankments.
• Geophysical Monitoring – Further trials and testing of the effectiveness in monitoring subsurface conditions for flood defences in the UK should be performed. Comparison of GPR and Geo-electric monitoring methods under UK soil conditions would be beneficial before such techniques are employed in actual asset management.
• ERT – It was not possible to test the effectiveness of this method on flood defences as part of this project. However, its potential has been identified in embankment monitoring in the rail industry and it seems worthy of further research and trials in a flood defence context.

8.6 Future developments in asset monitoring and inspection

It is not the aim of this work to make detailed predictions about the future of asset monitoring. However, it is useful to examine recent advances and highlight the scope for future developments in remote measurement, continuous monitoring, surveying and NDT. A brief discussion of potential advances and their impact on quantitative assessment of infrastructure assets is given below.

8.6.1 Technical advances

In terms of remote measurement, the technical equipment involved has improved greatly since its introduction and is likely to continue to improve over time. Image and data resolutions are now standard which would have been thought to be very high a decade ago. The accuracy of GPS and IMU units required for mobile surveys has followed a similar trend.

With regard to workflow and data processing for remote measurement data, this is an area that has shown great advances in the last decade or so. However, there is scope for further improvement particularly in terms of automation and feature extraction algorithms. It is in this area in particular that further advances would be of greatest benefit from a flood defence monitoring perspective.

For aerial LiDAR surveys, integration of point cloud data with the DSM for aerial surveys would be a technical advance that would be highly beneficial for monitoring surface deformations associated with asset condition. Software allowing a user to highlight an area of the DSM and ‘zoom’ into the raw point cloud data would allow asset managers to examine the detail of a potential surface anomaly.

Continuous monitoring employing electronic sensors and fixed cameras is an area where technological advances offer major opportunities. Current technology is limited or expensive to employ in most instances. Improvements and associated cost reductions
will make the use of continuous monitoring systems a much more viable method for flood defence monitoring in the same way as it is currently employed in monitoring dams and reservoirs. Advances in wireless sensor networks in terms of their accuracy, power consumption, robustness and reduced cost are likely to make them suitable for flood defence management. Power usage and supply is still a severely limiting factor for their use although the recent EA trash screen camera trial demonstrated a potential framework for their use.

Radio Frequency IDentification (RFID) tags is another technology that could offer a role in asset monitoring assuming that their cost and accuracy improve. A large number of these tags could be installed within assets and scanned periodically to detect internal movement and deformation. Currently this technology is too limited for use in flood defence monitoring but it is likely that these limitations will reduce over time.

For detailed inspection work there is a range of technological advances that could assist in quantitative assessment by inspection staff. Initial advances in this area are already evident and are likely to develop in the next few years. Mobile devices such as smartphones already offer the ability to perform a number of functions of potential relevance. For example, Figure 8.1 shows an image taken using a theodolite application available for the apple iPhone. This app allows the user to perform basic surveying operations and take geo-referenced imagery. Figure 8.2 shows a screenshot of the application taken from the developer’s website. The high growth and penetration in the smartphone market makes it likely that the hardware functionality and software available for these types of mobile device will continue to develop and improve into the near future.

![Figure 8.1. Image taken using iphone ‘theodolite’ application](image.jpg)
Another potential use of technology to assist in asset monitoring would be to utilise mobile broadband networks to allow operatives in the field to update asset data in real time from either a portable computer or smartphone type device.

A final method for use in detailed asset inspections combining mobile devices, GPS and mobile broadband would be to utilise the expanding field of augmented reality. Augmented reality applications overlay real time imagery with other datasets. For example, data from previous inspections could be tagged onto GIS data for an asset and could be viewed on-site overlaid with the current condition of the asset.

### 8.6.2 Social and environmental change

Policy and social issues are not a particular focus of this work which is primarily focussed on flood risk management from a scientific and engineering perspective. However, it is important not to concentrate solely on technological advances and consider how social and environmental change could also impact flood defence monitoring, even if only briefly.

There is increasing emphasis on public engagement in Flood Risk Management under the Environment Agency’s initiatives for improving Stakeholder Engagement. As regards the monitoring of flood defences it may be possible to develop public engagement through a range of approaches (e.g. introduction of flood defence reporting mechanisms by phone/text/internet) and this could lead to increased public reporting of faults with and failures of flood defences. The public would act as a method for increased monitoring and early detection of faults. Of course, it should be noted that the quality of the data reported may demonstrate high variability and could be a hindrance rather than a help at times. Nevertheless this potential for greatly increased monitoring of flood defence assets outside the standard visual inspection regime would offer major benefit.

Local ownership and stewardship of infrastructure assets could be expanded and have a broad impact on flood defence monitoring. In some areas, local community groups are already engaged and involved in monitoring and maintaining their local flood defences. These groups can regularly inspect and record asset condition and can be given training.
and assistance in this regard. The benefits are similar to those outlined for increased public engagement but with the additional advantage of having less variability and higher quality of data obtained. These issues could be explored further with representative bodies like the National Flood Forum.
9 Recommendations

This final chapter offers recommendations in five key areas; revisions to the standard visual inspection, introduction of a detailed asset inspection, the use of remote measurement in asset monitoring, continuous monitoring of flood defence assets using fixed cameras and sensors and critically, the changes to asset management systems that would be required to support these types of changes.

It is not the intention of this report to provide a rigid definition of how quantitative asset monitoring should or could be performed. Instead, these recommendations are intended to illustrate potential changes that could be introduced and what might be required to maximise the benefits from quantitative assessment of flood defence assets.

9.1 Changes to the visual inspection process

Some of the asset level methods outlined in this report could be employed as part of the standard visual inspection process. In particular, those not requiring highly advanced NDT equipment or significant additional resources would be candidates for inclusion. However, any change to the standard visual inspection should be carefully considered. It is critical that benefits arising from any change outweigh or at least counter any increases in inspection duration, complexity or cost. It is also important that any changes to visual inspection are properly integrated into asset management procedures and fully explained to inspection staff so that buy-in to the changes by staff is achieved.

Specific changes that could be incorporated into the visual inspection process with minimal cost and training but could provide benefit to asset managers are:

- Handheld GPS devices for geo-referencing of inspections and to allow inspector to mark and record areas of specific concern. This would be especially useful on larger assets to ensure that post-inspection remedial action can be carried out more easily.
- Basic measuring tools such as tape, callipers and rulers could be routinely employed by asset inspectors to record and log significant performance indicators such as cracks, rutting or holes identified in the asset surface. Quantifying these features will enable the inspector to detect any increase over time which could indicate a dynamic and ongoing mode of failure.
- Levelling tools for walls, revetment and other hard-surfaced defences could be a quick and easy method to measure, over time, any signs of movement in the asset associated with slipping or rotational failures.
- Formalisation of asset-based photography and integration with measuring devices such as photographic rulers or GPS and asset information systems such as NFCDD would be a relatively quick and easy method that could improve the quality and value of imagery produced.
- Marking tools for quantification of faults on asset surface. Paint/pens/etc.

9.2 The introduction of a detailed asset inspection process

In terms of the elements of a detailed asset inspection and what could be achieved through a combination of surveying and NDT based methods there is no overall list that would or should be applied in all instances. Many of the methods are expensive or time...
consuming to perform and can require specially trained operatives (or external consultants). Methods applied to a specific detailed inspection should be determined according to local conditions, asset history and expert judgment. For example, when a critical embankment has been shown to be prone to settlement, vermin infestation and poor soil conditions then it may warrant a crest profiling exercise using kinematic GPS in addition to some subsurface monitoring through either GPR or ERT. Alternatively, a gravity wall displaying signs of movement and loss of joint material may just require regular measurement, levelling and geo-referenced photography. Table 6 lists various methods that could be employed as part of a detailed asset inspection describing their utility, constraints and applicability.

The use of kinematic GPS for crest height and detailed surveying is going to be a very important for embankment monitoring in the future. It is understood that trials are already being undertaken by a number of groups involved in embankment monitoring.

As stated in section 2.7, a recent desk study commissioned by the EA provided a framework for how this level of asset monitoring could function and how it might fit into the overall asset management programme. The framework proposed seems to be an appropriate solution and this report will not comment further in relation to the structure and implementation of a detailed asset inspection from an asset management perspective.
Table 6. Table of surveying and NDT methods appropriate for a detailed asset inspection

<table>
<thead>
<tr>
<th>Method / Technique</th>
<th>Benefits</th>
<th>Limitations</th>
<th>Applicable assets</th>
</tr>
</thead>
</table>
| Kinematic GPS      | Can survey surface geometry to a very high level of accuracy.  
- Backpack mounted version can be operated by single operative and produce crest profiles over large assets quickly.  
- GPS mounted in mowing equipment has the potential to profile entire asset surface without additional resource requirements.  
- Can be used to profile large faults e.g. slip circles in embankment. | - Equipment is relatively expensive.  
- Requires connection to GSM or two receivers for kinematic corrections used.  
- Requires a clear view of satellites.  
- Some data processing and analysis may be required.  
- Requires continuous access to traverse crest. Vertical walls may be problematic in this regard. | Embankments Gravity Walls Revetments |
| GPR                | Can detect sub-surface performance indicators.  
- Identification of voids caused by geotechnical issues or vermin.  
- High penetration and accuracy in concrete, asphalt and masonry.  
- Non-destructive and does not require extensive setup and calibration | - Limited accuracy and penetration in heavy, clayey soils.  
- Expensive and requires training to employ in the field.  
- Data produced requires expert interpretation.  
- Can produce false-positives.  
- Cannot be easily setup and operated by a single operative. | Embankments Gravity Walls Revetments Backfill material |
| ERT                | Can detect sub-surface performance indicators.  
- Identification of voids caused by geotechnical issues or vermin.  
- Highlights areas of excessive moisture within sub-surface which could indicate seepage or piping.  
- More suited to soil conditions typically found in flood defences and their foundations than GPR | - Expensive and requires training to employ in the field.  
- Data produced requires expert interpretation.  
- Accuracy of results for flood defence monitoring requires further research.  
- Requires multiple trained operatives to setup and calibrate. | Embankments Backfill material |
| Measurement of key performance indicators | Low cost and requires minimal equipment and training.  
- Acquires quantitative data on performance features quickly.  
- Can easily be integrated with photography to produce images with quantitative data | - Can be difficult to measure features accurately on embankments due to changes in vegetation  
- Without geo-referencing may be difficult to ensure that repeated measurements assess identical features | All |
| Use of levelling devices | Simple, easy to use device  
- Quickly assesses wall level or slope angle.  
- Low cost  
- Logging of data enables detection of change over time. | - Only measures level or angle over a small area  
- Multiple measurements required for large assets.  
- For change detection may require fixed reference points for accurate assessment. | Vertical Walls Revetments (contiguous only) |
| Fixed point photography | Simple and fairly accurate method for acquiring comparative imagery for an asset.  
- Can be carried out with minimal training and equipment  
- Can acquire quantitative data with additional measurement | - Requires a fixed reference point to be setup  
- Multiple points needed for full coverage of an asset  
- A tripod is required to ensure fixed viewpoint is accurately used for each image | All |
| Geo-referenced photography | Image location is recorded.  
- Staff can locate feature easily on repeated inspection/remedial work. | - GPS position only accurate to around 3m  
- Cannot extract quantitative measurements from imagery | All |
| Ultrasonic Testing (UT) / Pulsed Eddy Current (PEC) | Can measure thickness of sheet pile.  
- Detects subsurface indicators of corrosion and ALWC.  
- Non-invasive and non-destructive. | - Expense of equipment  
- Requires processing and interpretation by a highly trained operative  
- UT requires a clean, smooth surface | Sheet Pile Walls |
Remote measurement, and in particular airborne remote measurement, has been shown to be capable of assessing asset geometry over large areas very rapidly. LiDAR and photogrammetry have been identified as being the methods most suited to flood defence monitoring though each has its limitations. In order to gain accurate assessments of geometry and particularly crest height, high-resolution data is necessary. To monitor asset geometry for signs of failure and deterioration associated with surface deformation requires very high-resolution data.

To date, LiDAR has been the preferred method employed for terrain mapping by the EA, Figure 9.1 shows the UK coverage of LiDAR data categorised by grid resolution of the DSMs available. For asset monitoring purposes a grid size of less than 1m is generally required. It can be seen from the diagram that there is currently a very limited set of data available at a sufficiently high resolution for asset monitoring purposes.

![Figure 9.1: UK LiDAR coverage classified by grid resolution – from left to right 2m, 1m, 0.5m, 0.25m](taken from www.geomatics-group.co.uk (accessed 05/02/2010)

There would need to be a huge increase in the amount of aerial surveying carried out by the EA if remote measurement was to be employed as the means to intelligently target visual inspections. Additionally, if LiDAR is to be more greatly utilised in flood defence asset management then it is important to consider the practical and logistical impacts and compare the technology against its competitors. Table 7 shows the various options for monitoring in terms of costs associated with them and their relevant benefits.

![Table 7. Comparison between high resolution LiDAR and selected competing technologies with reference to [Scott et al, 2005]](monitoring_table.png)

<table>
<thead>
<tr>
<th>Monitoring Method</th>
<th>Description and deliverables</th>
<th>Work Rate (km/day)</th>
<th>Data Processing</th>
<th>Unit Cost (£/km)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Land Survey (Single team)</td>
<td>Standard flood defence asset survey and level survey (including cross-sections, long sections and spot levels)</td>
<td>1</td>
<td>1 week</td>
<td>2000</td>
</tr>
<tr>
<td>Land Survey (Separate teams)</td>
<td>Standard flood defence asset survey and level survey (including cross-sections, long sections and spot levels)</td>
<td>1.5</td>
<td>1 week</td>
<td>1750</td>
</tr>
<tr>
<td>Fli-Map (full)</td>
<td>Video MPG, Cross-section, Long section, Spot levels, Contour level, Raster level</td>
<td>70</td>
<td>6 weeks</td>
<td>1000</td>
</tr>
<tr>
<td>Fli-Map (minimum)</td>
<td>Video MPG, Long sections, Spot levels</td>
<td>70</td>
<td>6 weeks</td>
<td>500</td>
</tr>
<tr>
<td>Sensor network</td>
<td>Network mesh positions for MEMS devices. Movement and velocity values for each node in the network (if any)</td>
<td>Network size</td>
<td>Real-Time</td>
<td>UNKNOWN</td>
</tr>
</tbody>
</table>

Note: Initial installation costs for a MEMS type network will be very high but operating costs once installed would be very low in comparison to other monitoring methods.
It should be noted that a sensor network also offers the ability for continuous monitoring without requiring an additional survey to be carried out. However, the initial setup and initialisation of the network will be significantly more expensive and time consuming than its competitors.

Aerial photogrammetry has been shown to be an alternative and effective means for monitoring assets over larger areas with similar accuracy to that achieved with LiDAR. The high-resolution imagery that can be produced enables the identification of surface condition features that are not detectable by LiDAR. It may be best suited to monitoring those types of asset not best suited to monitoring by airborne LiDAR such as slender wall type structures and narrow embankments. Advances in camera technology and improvements to processing software have the potential to make aerial photogrammetry a useful tool for asset management.

MLS such as the Lynx Mobile Mapper recently acquired by the Geomatics Group offer a relatively inexpensive platform for acquiring high resolution and highly accurate LiDAR data. The data produced does not require conversion to DSM format with the associated loss of detail that can be a major problem in an asset monitoring context. However, access to asset locations is an issue and MLS will not be possible for all assets. Water based platforms may be a solution for defences close to the channel or coastline.

### 9.4 Continuous monitoring of critical infrastructure

Methods and technologies for monitoring asset condition on a continuous or regular basis have been outlined throughout this report. They fall into a few broad categories: fixed cameras, motion sensors, moisture sensors, positional sensors and measurement gauges. All have to be installed on-site and some require invasive work to install them within the asset. Installation is often an expensive procedure and their use is only warranted for the more critical assets (in terms of their condition, environment or consequences of their failure).

The other main areas of concern regarding their use are in terms of power supply and consumption and the accuracy of the data they produce. MEMS devices seem to offer some potential due to their small size and low power usage and fixed cameras have already been shown to be a viable monitoring method from the EA’s trash screen camera project. The technology used in that project can be adapted to create multiple sensor arrays combining cameras with other sensors. Power usage issues could be mitigated by utilising an alarm-based approach rather than continual data logging and transmission.

It is recommended that further research and actual field trials should be carried out to establish whether the installation of MEMS-type devices and sensor arrays is a practical and effective solution for flood defence monitoring. Research to date indicates that logistical and cost based issues limit the applicability of continuous monitoring options to only the most critical of flood defence assets subject to extreme and dynamic loading conditions and where the potential for rapid and catastrophic failure exist. However, the rate of improvement in camera- and sensor-based technologies combined with associated cost reductions make this an area of rapidly increasing viability.
In addition, work done and ongoing at the Ijkdijk testing facility in The Netherlands (www.ijkdijk.eu) and under the EU UrbanFlood project (www.urbanflood.eu) demonstrates the type of research needed in this field and the quality of results possible.

‘The UrbanFlood project will create an Early Warning System framework that can be used to link sensors via the Internet to predictive models and emergency warning systems. The data collected from the sensors will be interpreted to assess the condition and likelihood of failure; different models will be used to predict the failure mode and subsequent potential inundation in near real time. Through the Internet, additional computer resources required by the framework are made available on demand. The project includes three pilot sites to apply and validate at full scale the technology being developed in the project: Amsterdam (Netherlands), Boston (UK) and St Petersburg (Russia).’ (Simm et al, 2011).

‘The instrumentation for embankment monitoring has been selected on the basis of previous experimentation and comparison of instruments installed in full scale dike failure tests in the Netherlands (Ijkdijk). Installed in CPT holes were

- Dutch developed MEMS modules (GeoBeads) able to detect local tilt, pore pressure and temperature, the latter as a proxy method for detecting water flow
- Two types of US-Canada developed Shape Acceleration Arrays able to measure three-directional soil deformation profile and one type also able to detect pore pressure

In addition, sensor enabled-geotextile strips based on fibre optic sensing technology, able to detect soil strain by distributed light back-scattering, were installed along the entire 300m in the crest and front slope of the embankment. This technology allows longer stretches of embankment to be monitored at low cost.

The gathered data is being used to detect anomalies, supported by an Artificial Intelligence system. If an anomaly is detected, this then triggers assessment of the likelihood of levee breach. If breach is likely, the consequences in terms of flood propagation and damage in the defended urban area are assessed via high speed computer modelling.’ (Simm et al, 2011).

Simpler devices such as tell-tales and gauges would seem to offer some benefits without significant overheads and costs associated with their use and installation. These would however require some form of data logging or communication to be considered continuous monitoring devices rather than in-situ measurement tools to be checked as part of the regular inspection regime.

### 9.5 Data management, application and retention

In this final section a most critical issue concerning quantitative assessment of flood defence assets will be discussed. In order to fully utilise the potential of the various methods and techniques described in this report it is crucial to improve the management and retention of data. Without this, many of the benefits of monitoring and assessment cannot be fully realised. The various methods of remote measurement, asset surveying, NDT and continuous monitoring described produce a wealth of data, much of which is not currently recorded under current asset management systems. Data could be simply added as unformatted attachments (e.g. notes or images) which would ensure retention.
but would make it difficult to apply the knowledge gained in flood risk analysis and asset management processes.

In terms of remote measurement, large data-rich imagery and terrain models are produced. This requires processing and analysis and it is essential that a method exists for updating asset geometry from this data. Ideally, a record of asset geometry for each remote sensed survey should be both retained and accessible to asset managers if the maximum benefits of employing remote measurement for asset monitoring are to be gained. It is recommended that aerial photogrammetry and LiDAR should be integrated as a viewable layer in the asset management system. The IA3 database developed as part of the TE2100 project allowed this functionality (though only as a limited cross-sectional profile in terms of LiDAR data). It also included menu options for viewing any associated asset level photography and other asset specific data (cross-sectional profiles, inspection records, etc) as shown in Figure 9.2. Only if this is done will the data collected be able to be used for its main purpose – decision making to improve flood risk management.

The current NFCDD also contains some of this functionality but has some limitations in terms of integrating data from some of the methods proposed in this report. An example of this would be in relation to the retention and application of crest profiles for assets. Both LiDAR and Kinematic GPS have been shown to be capable of producing sufficiently accurate crest profiles for assets. However, NFCDD currently assigns a single attribute of crest height for each asset representing the minimum crest height for the entire asset. The position of this low point on the asset’s surface is not recorded. Therefore, the majority of the data collected in a crest profile would be lost when input to NFCDD. It would be possible to retain this data by attaching the profile as an image or
data file to the asset but there would not be a mechanism for applying the profile in risk analysis.

It is recommended that currently ongoing development of a system for asset management by the EA should consider potential data management issues in relation to asset monitoring datasets that are both currently available and likely to be available in the near future. For example, if remote sensed data is to be used for asset profiling and monitoring to a greater degree then these datasets should be fully integrated into any future asset management system. These issues should be addressed in any work on asset performance tools.

To maximise benefits of quantitative assessment requires the incorporation of a sufficiently detailed Asset Information Model (AIM) analogous to the Building Information Model (BIM) models now becoming commonplace in the construction industry.
References


Rowsell P and Owen J. (2009): Earthwork Monitoring - Desk Study to Establish State of the Art in Infrastructure Health Monitoring, University of Nottingham P/O 543308


Appendices
A Embankment LiDAR Simulator

A large number of simulations were carried out using the Embankment Simulator software produced during the research but it is only possible to include a couple of brief examples here. Figure A.1 shows an additional simulation using the coordinates and dimensions for the embankment at Silverdale near Nottingham that was described in chapter 7 of the main body of the report. In the example shown, extensions to the basic simulator described in section 7.1 were utilised to simulate a much larger scale deformation of the asset surface.

![Figure A.1 - Simulation of large failure at Silverdale](image)

The simulated embankment with failure highlighted is shown in Figure A.1 (left). The failure consists of large scale slipping or settlement affecting the inner slope at the tight bend in the embankment. There is also a lowering of surface on the crest and top of the outer slope at the southern extent of the large deformation. Figure A.1 (middle) shows the difference at each point in the datasets between two simulated surveys of the embankment with and without failure. The noise in the dataset (0.10m) makes it difficult to identify the failure clearly in this image. Figure A.1 (right) shows the slope difference between points in the datasets. The failure is greatly exaggerated and clearly identifiable using this method. (Slope Difference refers to a method of comparison between two datasets whereby the slope between points in the each dataset is calculated and the...
difference between these slope values is used to produce a new dataset representing the slope difference.

Figure A.2 shows a simulation of a section of another embankment investigated during the research at Colwick near Nottingham and described in appendix C. This example also illustrates an enhancement from the original simulation as the ground levels of the inner and outer slopes of the embankment are at different levels. This change was included in order for the simulator to model embankments more realistically.

Figure A.2 (left) image shows the embankment without failure and the right image includes a small depth surface deformation (length = 3m, width = 1m, depth = 0.5m) such as that which might be associated with a large circular slip. The failure cannot be clearly seen in the right hand image due to the resolution of the DSM data (1m gridded).

Figure A.2 - Simulation of embankment section at Colwick (Left - No fault.  Right – Fault at southern end (bottom of the figure) of embankment)

In this example a noise level of 0.2m was used to simulate the length of grass cover often inspected for this defence asset. Figure A.3 shows the point and slope differences calculated for the embankment with and without the failure. In this instance
the point difference is clearer in identifying areas of potential concern but does still not clearly indicate the actual location of failure.

Figure A.3 - Simulation of embankment section at Colwick (Left – Point difference between datasets. Right – Slope difference between datasets)

Figure A.4 shows the slope difference between datasets rotated to illustrate the extent of the slope differences more clearly. From this viewpoint, the actual area of failure is more identifiable but it is clear that the noise in the dataset caused by excessive length of vegetation cover makes it difficult to assess surface deformations with this resolution of data.

Figure A.4 - Simulation of embankment section at Colwick: Cross-sectional view of slope difference between datasets
B  Analysis of LiDAR datasets

A range of LiDAR data was examined during the project. The majority of this data was in the form of Aerial Digital Surface Models (DSMs) though some raw point cloud data from Terrestrial Laser Scanning (TLS) and Mobile Laser Scanning (MLS) surveys was also analysed. In this section some examples of LiDAR data (and associated aerial photography) are shown with brief explanation of any key points they highlight.

An initial example of the types of LiDAR datasets investigated and methods for detecting change in the datasets is shown in Figure B.1 to Figure B.5. The data shown was obtained from the Channel Coast Observatory website (www.channelcoast.org) operated by the Southern Coastal Group in the UK. Figure B.1 shows the area of interest with the aerial photography overlain on the LiDAR DSM which is shown in Figure B.2.

Figure B.1 - Integration of LiDAR DSM and photogrammetry data

Figure B.2 - LiDAR Digital Surface Model
Figure B.3 shows the DTM produced from the DSM data by the automated filtering and removal of surface features intended to produce a model of terrain without surface features such as buildings or vegetation. In order to assess methods for comparing LiDAR datasets it was decided that a comparison between The DSM and DTM datasets would be an ideal method as it could be guaranteed that issues of data resolution and survey errors could be eliminated. The comparison is instead an analysis of the DTM production algorithms.

Figure B.3 - Digital Terrain Model generated from LiDAR DSM

Figure B.4 shows the difference between points in the DSM and DTM. The housing in the lower left of the image is clearly removed as intended along with the trees in the top left of the image. A number of other differences are shown at the cliff edge on the right hand side of the image where the DTM production algorithms have removed some detail. The sharp edges present in the DSM at the cliff edge have been assumed to represent surface features rather than features of the terrain itself. A similar effect can be noted in the smoothing out of the fluvial channel at in the top left of the imagery below the trees.

Figure B.4 - Point difference between DSM and DTM
previously highlighted. Point difference is a highly effective method of accurately comparing the difference between two LiDAR DSMs and can be used to get a quantitative assessment of the change in surface geometry such as the dimensions of a slip or area of settlement. However, small scale changes such as those indicative of the initiation of failure modes may not be visible using the point difference method especially for lower resolution DSM data. Instead a method which can exaggerate and highlight potential areas of change representative of failure was needed. Assessing the slope difference between two datasets was identified as a potential solution.

Figure B.5 - Slope difference between DSM and DTM

Figure B.5 shows the slope difference between the DSM and DTM datasets. The differences are greatly exaggerated enabling the easy identification of change between the two. The values produced cannot be used to provide a quantitative assessment of change but can be highly effective in identifying areas of potential concern for further investigation. However, as shown in the results from the simulation shown in appendix A and section 7.1, noise in the dataset will be amplified by this method making it impractical for detecting actual change. A combination of point and slope difference analysis is the most effective means for detecting changes to asset geometry from LiDAR DSMs.
C Trial of low tech monitoring solutions

Trials were carried out for some of the basic methods for asset monitoring as part of a detailed visual inspection. These included a range of techniques and methods that did not require expensive equipment or training and could be carried out by any trained asset inspector. The methods employed during the trials were:

- **Standard GPS** – For logging the inspection route and geo-referencing any key findings.
- **Digital Camera** – For producing images of asset condition over time. Also used to record asset geometry and condition from fixed reference points to maximise potential for detecting change from repeated inspections.
- **Tape Measure** – For quantifying the dimensional properties of surface features of interest.

Trials of the methods were undertaken at a number of locations in the Nottinghamshire area. The main trial site monitored was at Colwick on the outskirts of Nottingham. Regular inspections were carried out at the site from June 2008 until June 2010 for a number of assets. Four zones were chosen and monitored during the trial. Figure C.1 shows the zones superimposed on satellite photography taken from Google Earth. The blue lines shown in the image are track data taken from the handheld GPS during the trial and waypoints logged into the GPS unit are shown as flags and descriptions in Figure C.1.

![Figure C.1 - Main trial site showing three zones monitored. Colwick, Nottingham](image)

Table C.1 gives an overview of each zone monitored in the trial at site 1 listing the asset types found in each zone and an overview of key findings and asset condition during the trial. No vertical wall assets were present at this trial site and were therefore not a part of this trial. It should be noted that the defences within the trial site are being upgraded as part of the Trent Left Bank Flood Alleviation Scheme during 2010-2011.
Table C.1 - Details of zones monitored at main trial site

<table>
<thead>
<tr>
<th>Zone</th>
<th>Assets</th>
<th>Details</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>Embankment</td>
<td>Large raised embankment. Mid-section showed signs of rutting along crest. Monitored using two fixed reference points, tape measure, close-up asset photography and GPS.</td>
</tr>
<tr>
<td>B</td>
<td>Sloped Revetment Embankment</td>
<td>Sloped revetment (in-situ concrete and rock) defends channel sides downstream of large sluice gate on river Trent. Monitored using photography and tape measure. Some signs of deterioration of surface material and growth of vegetation on surface.</td>
</tr>
<tr>
<td>C</td>
<td>Embankment Reno-mattress Culvert (disused)</td>
<td>Embankment protecting residential housing from flooding from river Trent. Reno-mattress used to support disused culvert at eastern end of zone and protect against erosion. Poor vegetation identified on inner slope of embankment caused by local residents dumping garden waste on slope.</td>
</tr>
<tr>
<td>D</td>
<td>Embankment Culvert (disused) Trash screen(disused)</td>
<td>Embankment with gravel crest protection regularly used for recreation. Residential properties directly behind outer face. Retired drainage channel located approx. 10m from outer slope with concrete culvert and trash screen. Photographed at regular intervals; embankment in excellent condition and no signs of deterioration identified.</td>
</tr>
</tbody>
</table>

Zone A was the main zone monitored during the trial. This stretch of raised embankment was monitored over 15 times during the trial period. Other zones were monitored less frequently (around 4-8 times) but still at far smaller intervals than would be required under EA’s visual inspection regime. Increased monitoring at zone A was warranted due to the identification of a changing performance indicator in this area. Rutting of the crest and top of the outer slope of the embankment was observed during the detailed inspection on 06/12/2008. Rutting and loss of grass cover was deduced to be caused by third party interference with the asset at this point. The rutted area was directly behind a goalpost in a recreation area protected by the defence. It is thought that damage was caused by the regular retrieval of footballs from the other side of the defence. The presence of this feature was communicated to the local asset inspection teams but was not considered to be a major concern due to its small relative size in relation to the dimensions of the overall asset, its limited reduction in crest width and the infrequency of hydraulic loading of the asset.

To monitor this feature and any change to it two fixed points were designated and used to collect fixed point imagery of the embankment around the area of rutting. Imagery from one of the fixed reference points used at zone A is shown in Figure C.2. The area of rutting is visible along the crest of the embankment in the middle of the images between the two trees present.
Note that image 5 was not taken from the exact fixed point as used in the other pictures. This was due to snow cover making it impossible to locate the fixed point exactly. It highlights a potential difficulty in this type of fixed point photography in all weather conditions.

Figure C.3 shows close up images of the rutting taken throughout the trial from different angles and at different time. In the top left image the football pitch thought to be the source of the traffic causing the rutting can be clearly seen. In the bottom left image, the process of measuring the length of the rut can be seen. Results from the quantitative assessment can be found in Table C.2.
Figure C.3 - Close up images of rutting on crest slope in zone A

Table C.2 - Selection of measurements taken during trial of rutting on bank crest in zone A

<table>
<thead>
<tr>
<th>Date</th>
<th>Length (along crest)</th>
<th>Width (Perpendicular to crest)</th>
<th>Depth</th>
</tr>
</thead>
<tbody>
<tr>
<td>07/04/09</td>
<td>0.92</td>
<td>0.36</td>
<td>0.34</td>
</tr>
<tr>
<td>22/04/09</td>
<td>0.97</td>
<td>0.38</td>
<td>0.37</td>
</tr>
<tr>
<td>22/05/09</td>
<td>1.02</td>
<td>0.44</td>
<td>0.42</td>
</tr>
<tr>
<td>12/07/09</td>
<td>1.08</td>
<td>0.42</td>
<td>0.45</td>
</tr>
<tr>
<td>09/01/10</td>
<td>0.98</td>
<td>0.37</td>
<td>0.44</td>
</tr>
<tr>
<td>06/06/10</td>
<td>1.03</td>
<td>0.40</td>
<td>0.45</td>
</tr>
</tbody>
</table>

This exercise and the data shown in Table C.2 demonstrate both the potential utility and difficulties in quantitative assessment of this type of performance feature. Accurately measuring the dimensions of the feature using just a measuring tape is not easy. The edges of the rutting are ill-defined for highly accurate assessment on repeated surveys. However, the figures shown identify a definite increase in the dimensions of the deformation over time (the data highlighted in the table is thought to be in error as it was during heavy snowfall).

Example images taken at the other zones in the trial are shown in Figure C.4 to Figure C.6.
14/06/08 – Reno Mattress supporting culvert
14/06/08 – Recently mowed slope showing bare patches of vegetation

13/06/09 – Reno Mattress from channel side
13/06/09 – Slope showing poor vegetation and presence of dumped garden waste

Figure C.4 - Selected images taken from zone B during the trial
22/04/09 – Heavily vegetated revetment from fixed point C

14/03/10 – Damage to revetment directly below fixed point C

22/04/09 – Low water levels in Trent reveal temporary ‘rock island’

14/03/10 – Loss of grass cover identified on slope on opposite side of channel from fixed point C

Figure C.5 - Selected images taken from zone C during the trial

11/04/10 – Embankment looking east from fixed point D showing presence of varied vegetation on outer slope and proximity of residential housing.

11/04/10 – Embankment looking west from fixed point D showing presence of trees at toe of outer slope and crest protection.

Figure C.6 - Selected images taken from zone D during the trial
D Case Study – Environment Agency trash screen camera trial

In order to improve the monitoring and management of trash screens at culverts the EA decided to trial the use of fixed cameras to monitor a number of sites. High resolution cameras with night vision capability were installed across a range of sites during the trial. Cameras were mounted to fixed poles with a viewpoint of the asset(s) to be monitored. During the trial the number of sites was gradually increased and some additional types of asset were included (e.g. flood gates). Cameras were powered by high specification rechargeable batteries which were charged by photovoltaic cells mounted on the top of the camera mount pole.

Power usage by the cameras made it impractical to monitor the sites continuously. It was determined that the cameras should take and transmit two images per day (one at day and one at night). In addition, an inspector can request an ad-hoc image at any point by sending a text message from any GSM mobile phone. Figure D.1 and Figure D.2 show images from the IT system used to manage and control the remote cameras.

![Figure D.1 - Screenshot of VideoCenter software used to manage and store trash screen imagery showing fixed camera sites and images for Midlands region. (EA and Computer Network Ltd)](image_url)
Meetings and interviews were held with EA staff and external contractors involved in the project. It was determined that the configuration and infrastructure used for the trash screen camera trial could be adapted for the monitoring of other flood defence assets and that the cameras could potentially be supplemented with additional sensors. The battery, solar cells, transmitter/receiver and IT infrastructure used in the trial could be employed to manage and control multi-sensor arrays (assuming that the power requirements of the combined camera and sensors could be satisfied by the battery/solar cell configuration).

Figure D.3 gives an example of monitoring other asset types using the system along with its night vision capability. Figure D.4 shows images taken from one of the camera sites in the trial over a four month period illustrating the detection of changes to the local environment and vegetation that could be useful in the monitoring of other asset types such as vegetation condition for earth embankments.
Figure D.4 - Selection of images taken from one of the trash screen cameras used in the trial over a four month period
The Thames Estuary 2100 project (TE2100) was a long term, holistic study of flood risk in the Thames Estuary for the next 100 years. The project integrated data from a range of sources including aerial surveys (LiDAR, Radar and photography), performance based visual inspections, detailed geotechnical surveys and historical records for the area. Data from these sources was used to develop a GIS database referred to as the IA3 database.

The database enables the incorporation of aerial survey data into the asset management system and allows the user to browse and search the database across a range of categories, e.g. crest height, defence condition or asset type (see Figure E.1). Aerial photography of the defence line is included in the database and can be overlaid on the asset data to assist the asset manager in analysing the condition and likely performance of an asset (see Figure E.2). Elevation profiles for the defence line were extracted from high resolution helicopter mounted LiDAR surveys (0.25m DSM). This was integrated into the database as three points on the defence cross-section representing elevation data for inner toe, crest and outer toe at regular (10-20m) intervals. The automated extraction of this data proved to be difficult to achieve due to the high presence of buildings and other structures in close proximity to the defence line at many points in the estuary.

The IA3 database covered the entire tidal range of the Thames (Teddington Lock – Shoeburyness) though aerial survey data was only acquired in the outer estuary due to low altitude flight restrictions over central London. Figure E.3 shows a screenshot of the database illustrating the area covered by the database.

DSM data from the high resolution LiDAR surveys carried out was acquired and compared with previous DSM data for the area. Examples from the dataset were used in the main body of the report. Figure E.4 shows an example of the quality of the 25cm DSM for an area on the North Western edge of Canvey Island. Embankments, trees and roads can be clearly identified in the data. Figure E.5 shows DSM data from a previous LiDAR survey of the area carried out in 1999 using a 2m grid resolution. Very little detail can be identified in the data and the geometry of the large embankment defence is unclear. The difference in recorded elevation for a point on the embankment is shown in the figures as the pixel value in the Identify window. It shows the height at that point in millimetres and indicates a difference of almost a metre between the two datasets. This again backs up the conclusion that low resolution DSM data is of little use in assessing asset geometry and detecting change.
Figure E.1 - Screenshot from IA3 database generated from TE2100 data collection
Figure E.2 - IA3 Database. Close up of individual asset in poor condition showing aerial photography. Shoeburyness, Essex.
Figure E.3 - Screenshot of IA3 database showing crest heights in the Thames Estuary
Figure E.4 – 0.25m DSM LiDAR dataset for NW edge of Canvey Island (Flown March 2006)
Figure E.5 - 2m DSM LiDAR dataset for NW edge of Canvey Island (Flown March 1999)
F  Crest profile data from Kinematic GPS trials

Figure F.1 - Enlarged version of crest profile data produced from Kinematic GPS trials 1 and 2 at Silverdale, Nottingham
Figure F.2 – Enlarged version of crest profile produced from Kinematic GPS trial 3 at Hayling Island, Portsmouth
G Summary of potential technologies and methodologies for flood defence asset monitoring

G.1 System Level Surveys

<table>
<thead>
<tr>
<th>Technology</th>
<th>Coverage</th>
<th>Accuracy</th>
<th>Benefits</th>
<th>Limitations</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aerial Photogrammetry (top-down)</td>
<td>System-&gt;Sub-reach</td>
<td>High (5cm/pixel)</td>
<td>- Highly accurate in assessing x and y dimensions of assets</td>
<td>- Low accuracy in the z dimension</td>
</tr>
<tr>
<td></td>
<td>depending on altitude</td>
<td></td>
<td>- High resolution images of assets systems can be easily acquired</td>
<td>- Limited view of asset slopes or faces</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>- Can be used in conjunction with LiDAR to create a highly accurate 3D model of asset system</td>
<td>- Effected by cloud cover</td>
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<td></td>
<td></td>
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<td>- Environmental conditions limit use frequently</td>
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<td></td>
<td></td>
<td>- Does not produce a true crest/asset profile where there are trees, buildings or other obstructions</td>
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<td></td>
</tr>
<tr>
<td>Oblique Aerial Photography (bird’s eye)</td>
<td>Reach-&gt;-Sub-reach</td>
<td>High</td>
<td>- Only method capable of examining underwater features</td>
<td>- Crest elevation difficult to accurately assess</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>- Highly accurate in terms of the requirements of the project</td>
<td>- Camera angle obscures view of some features</td>
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<td></td>
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<td></td>
<td></td>
<td>- Multiple shots required for all sides of assets</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>- Cost to cover a large area such as an asset system</td>
</tr>
<tr>
<td>Satellite photography</td>
<td>System</td>
<td>Low</td>
<td>- Can produce high quality images of whole asset systems</td>
<td>- Not very useful in identifying problems at the asset level</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>- Can be used to initiate analysis and determine areas</td>
<td>- Cannot produce images under cloud cover</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>for further investigation</td>
<td>- View of assets obscured by vegetation cover</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>- Number of satellites already in place and acquiring such images as a matter of course</td>
<td></td>
</tr>
<tr>
<td>Aerial Near IR Photography</td>
<td>System-&gt;Sub-reach</td>
<td>High</td>
<td>- Detects extends of vegetation more clearly than standard photography</td>
<td>- Less useful than standard photography in identifying non vegetative features</td>
</tr>
<tr>
<td></td>
<td>depending on altitude</td>
<td></td>
<td>- Potential for identification of type and state of vegetative features</td>
<td>- Only truly useful in combination with standard photography and/or other methods such as LiDAR</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>- Potential for highlighting areas of greater and lesser moisture content</td>
<td></td>
</tr>
<tr>
<td>Airborne LiDAR (standard)</td>
<td>System-&gt;Reach</td>
<td>High</td>
<td>- Most accurate system level method for assessing height elevation</td>
<td>- Less accurate than photography in x and y dimensions</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>- Can produce an estimation of both ground surface and surface feature elevation such as vegetation</td>
<td>- Requires a large number of overlapping flight paths to be run</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>- Much less labour and time intensive than traditional ground based surveying of assets</td>
<td>- Requires extensive data processing to provide useful data</td>
</tr>
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<td>- Does not show non-positional damage or deterioration</td>
</tr>
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<td></td>
<td></td>
<td></td>
<td></td>
<td>- Signal is affected by vegetation requiring software filtering process to eliminate ground features</td>
</tr>
<tr>
<td>Airborne LiDAR (high density e.g. Fli-Map)</td>
<td>System-&gt;Reach</td>
<td>Very High</td>
<td>- Even higher accuracy and resolution than standard LiDAR</td>
<td>- Less coverage than standard LiDAR thus increasing cost and time for surveying</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>- Can identify thin features such as walls that may not be identified under standard LiDAR</td>
<td></td>
</tr>
</tbody>
</table>
| Ground based LiDAR | Reach->Sub-reach | Very High | - Provides greatest accuracy and resolution  
- Can view assets from angles that are obscured from a aerial survey or under heavy vegetative cover  
- Potential for detailed assessment of inner faces of assets by boat. | - Time consuming and expensive  
- Requires vehicular access to assets that may prove problematic in many instances |
|-------------------|-----------------|-----------|-------------------------------------------------|---------------------------------------------------------------|
| Satellite InSAR   | System          | Low       | - Not affected by cloud cover  
- Can produce images 24 hours a day  
- Systems already in place and use for DEM modelling and other applications  
- Longer wavelength based systems (e.g. p-band) can overcome or reduce problems with scattering caused by vegetation | - Signal is scattered by vegetation cover, a significant issue in terms of rural flood defences  
- Low accuracy in comparison to other system level methods  
- Longer wavelength systems more greatly affected by Faraday Rotation which reduces system accuracy and viability |
| Airborne InSAR    | System-Reach    | Medium    | - Higher resolution and accuracy over satellite based system  
- Not affected by cloud cover therefore can be used at high higher altitudes  
- Can be flown 24 hours/day  
- Longer wavelength methods not affected by Faraday Rotation | - Still adversely affected by vegetation coverage  
- Longer wavelength systems require regulatory approval for use  
- Still not as accurate as other airborne systems |
| Ground based InSAR| Reach->Sub-reach| High (relative assessment) | - Higher resolution and accuracy over satellite and airborne based systems  
- Can be used at night-time avoiding disruption and traffic issues  
- Longer wavelength methods not affected by Faraday Rotation or regulatory approval issues | - Access to assets by vehicle could be difficult in many instances  
- Repeated scans needed to get accurate data  
- Vehicle’s relative position to asset line must be highly consistent on each and every scan path |
| Side Scan Sonar   | Reach->Sub-reach| High      | - Only method capable of examining underwater features  
- Highly accurate in terms of the requirements of the project  
- Relatively inexpensive equipment in comparison to other system level techniques  
- Could utilise existing use by EA for fisheries management or channel assessment with little or no adaptation | - Can only produce an assessment of features below water line  
- Expensive in comparison to visual inspection of structures at low water (if possible)  
- Output may be affected by underwater debris  
- Shallow water channels may be unsuitable for this type of survey |
| GPS Network       | System          | Low       | - Can produce continuous system level monitoring for detecting structural movement  
- Very cheap to process and maintain once initial set up of GPS network in place  
- May be able to utilise existing UK GPS network | - Only method capable of examining underwater features  
- Highly accurate in terms of the requirements of the project |
## Detailed inspection and remote monitoring

<table>
<thead>
<tr>
<th>Method/Technology</th>
<th>Benefits</th>
<th>Limitations</th>
</tr>
</thead>
</table>
| **Fixed point photography and PF measurement** | - Simple methods to implement  
- Requires no expensive technology  
- A measured step forwards in formalising the inspection regime and increasing consistency | - Labour intensive inspection method  
- Training and technical knowledge on potential modes of failure will be likely to be required  
- Still requires judgement of inspection staff in order to determine elements for measurement |
| **Ground Based Laser Survey Equipment** | - Easy to use tool that does not require surveying experience  
- Enables overlay of reference elevation to ease identification of crest profiles  
- Provides accurate asset geometry without need for expensive topographical survey  
- Records and logs data automatically for transfer into NFCDD | - Expensive technology to provide to all inspection staff  
- Unknown if technology accurate enough to identify changes not visible through a standard inspection  
- Access issues may limit its effective use for many assets  
- Unsure if laser based technology is suitable for all structure types  
- Staff will require training  
- Accurate asset geometry may be useful but may not significantly improve performance assessment |
| **Thermal Imagery/Thermography** | - Can be used to identify sub-surface problems in many materials, especially concrete and masonry.  
- Can be used to detect voids and/or signs of seepage not possible under a visual inspection  
- Relatively easy to use in comparison with other NDT methods | - Does not detect deep sub-surface issues  
- Accuracy affected by material properties such as thickness and moisture content  
- Environmental conditions may adversely effect results  
- Expensive  
- Requires expertise in interpreting results  
- Only of greatest use for concrete structures |
| **Ultrasonic scanning** | - Can detect deep sub-surface flaws in structures  
- Can identify thickness of sheet pile  
- Can be used for detection of sub-surface honeycombing or cracks in concrete structures | - Difficult to interpret results without training and experience  
- Expensive equipment  
- Little use with earth embankments (most common liner defence structure) |
| **Ground Penetrating Radar** | - Highly suited to examining sub-surface detail of structures  
- Have been shown to detect geotechnical issues that are undetectable by visual inspection  
- Can be useful on all asset types | - Adversely affected with wet clayey soils (which are common in flood defences)  
- Generally uses bulky and expensive equipment unsuitable for use by inspection staff  
- Results require expert analysis |
| **Radiometry/Radiography** | - Can detect sub-surface damage  
- Differences in material condition and thickness throughout a material that are not visible can be identified | - Potential hazards of use (utilises x-rays and gamma rays) require effective training  
- Only really suitable for wall type structures  
- Expensive and difficult to use in the field by inspection staff  
- Results require post processing before interpretation can be performed |
| **Motion Sensor (accelerometer)** | - Can provide a profile of structural movement over time that is not possible through regular visual inspections  
- Relatively inexpensive and easy to install and calibrate  
- Can draw upon wide experience of use in dam and reservoir | - Accuracy of movement detection may be insufficient for purposes  
- Technology may be unsuitable for small flood defence structures  
- Used on its own it may not provide enough information on nature of problems |
### Inclinometer
- Can detect changes in angle and misalignment of structures that is not visible to the human eye
- Relatively inexpensive to implement
- Can be combined with other sensors (e.g., accelerometers, GPS, tell-tales) to produce a holistic view of structural change over time

### Tell-tales and gauges
- Simple methods to implement
- Requires no expensive technology except for potential telemetry for continuous monitoring
- Can be applied to specific areas of concern such as cracks or wall crests

### GPS Station
- Can detect position to a centimetre level of accuracy
- Well understood technology that is already in use for structural health monitoring
- Receivers have become much cheaper in recent years
- Can be used both at the asset or asset system level
- Could be combined with other sensors to provide a holistic view of changes to asset

### Real-time reflectometry
- Can detect deep slope movements not possible under a purely visual inspection
- Once installed should require little maintenance or calibration

<table>
<thead>
<tr>
<th>Assessment</th>
<th>Options</th>
</tr>
</thead>
</table>
| Inclinometer | - Can detect changes in angle and misalignment of structures that is not visible to the human eye  
- Relatively inexpensive to implement  
- Can be combined with other sensors (e.g., accelerometers, GPS, tell-tales) to produce a holistic view of structural change over time  
- Used on its own it may not provide enough information on nature of problems |
| Tell-tales and gauges | - Simple methods to implement  
- Requires no expensive technology except for potential telemetry for continuous monitoring  
- Can be applied to specific areas of concern such as cracks or wall crests  
- Requires accurate installation on asset  
- Lack of accuracy depending on placement and type of gauge  
- Without telemetry, which increases cost, it cannot provide continuous monitoring |
| GPS Station | - Can detect position to a centimetre level of accuracy  
- Well understood technology that is already in use for structural health monitoring  
- Receivers have become much cheaper in recent years  
- Can be used both at the asset or asset system level  
- Could be combined with other sensors to provide a holistic view of changes to asset  
- Inherent inaccuracy of GPS may be unsuitable for detecting small changes in position  
- Requires a clear view of satellites  
- Problems in placing receiver(s) in ideal location for detecting change  
- Used alone it may not produce a good assessment of ongoing problems |
| Real-time reflectometry | - Can detect deep slope movements not possible under a purely visual inspection  
- Once installed should require little maintenance or calibration  
- Invasive testing method that requires cables to be installed ground surrounding/forming structure  
- May not produce required accuracy for smaller structures found in flood defence |
G.3 Indicator / Asset Type Summary

<table>
<thead>
<tr>
<th>Visual Indicator / Asset type</th>
<th>Location</th>
<th>Description</th>
<th>Size (m)</th>
<th>Method and comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Crest Height 3.3.1</td>
<td>Crest</td>
<td></td>
<td></td>
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</tr>
<tr>
<td>Slight</td>
<td></td>
<td>X: any</td>
<td>RTK GPS Backpack mounted – Can combine with regular visual inspections. May not be accurate enough LiDAR with 0.125m grid. Vegetation a possible problem. May miss some features. Slope differences may improve accuracy Geo-referenced photography – accurate measurements difficult Photogrammetry – large amount of processing required, some manual. Vegetation can cause problems. Terrestrial Laser Scanning (TLS) – lot of work for just crest height, not practical for a significant length Mobile Laser Scanning (MLS) OK but possible problems with vehicular access</td>
<td></td>
</tr>
<tr>
<td>Minor</td>
<td></td>
<td>X: any</td>
<td>RTK GPS Backpack mounted – Can combine with regular visual inspections RTK GPS Vehicle (grass cutter) mounted – not possible on all embankments? LiDAR with 0.25m grid. Vegetation a possible problem. May miss some features. Slope differences may improve accuracy Geo-referenced photography – accurate measurements difficult Photogrammetry – Needs considerable processing but can be very accurate. Vegetation can cause problems. Terrestrial Laser Scanning (TLS) – lot of work for just crest height, not practical. May be better than LiDAR with large grid Mobile Laser Scanning (MLS) OK but possible problems with vehicular access. May be better than LiDAR with large grid</td>
<td></td>
</tr>
<tr>
<td>Major</td>
<td></td>
<td>X: 0.6+</td>
<td>RTK GPS Backpack mounted – Can combine with regular visual inspections RTK GPS Vehicle (grass cutter) mounted – not possible on all embankments? LiDAR with 0.5m grid. Vegetation a possible problem Geo-referenced photography – accurate measurements difficult Photogrammetry – needs considerable processing. Vegetation can cause problems. Terrestrial Laser Scanning (TLS) – lot of work for just crest height, not practical. Mobile Laser Scanning (MLS) OK but possible problems with vehicular access</td>
<td></td>
</tr>
<tr>
<td>Rutting 3.3.3</td>
<td>Crest / Slope</td>
<td>Wearing of crest or slope due to traffic (human or livestock)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Slight</td>
<td></td>
<td>X:0.1-0.3</td>
<td>RTK GPS Backpack mounted – Can combine with regular visual inspections LiDAR with 0.125m grid. Vegetation a possible problem. May miss some features. Slope differences may improve accuracy Geo-referenced photography – accurate measurements difficult Photogrammetry Terrestrial Laser Scanning (TLS) – lot of work, not practical for a significant length Mobile Laser Scanning (MLS) OK but possible problems with vehicular access</td>
<td></td>
</tr>
<tr>
<td>Minor</td>
<td></td>
<td>X:0.3-0.6</td>
<td>RTK GPS Backpack mounted – Can combine with regular visual inspections RTK GPS Vehicle (grass cutter) mounted LiDAR with 0.25m grid. Vegetation a possible problem. May miss some features. Slope differences may improve accuracy</td>
<td></td>
</tr>
<tr>
<td>Visual Indicator / Asset type</td>
<td>Location</td>
<td>Description</td>
<td>Size (m)</td>
<td>Method and comments</td>
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</tr>
</tbody>
</table>
| Major                        |          |             | X: 0.6+  
  Y: 1.0+  
  Z: 0.3+ | Geo-referenced photography – accurate measurements difficult  
  Photogrammetry – Needs considerable processing but can be very accurate. Vegetation can cause problems.  
  Terrestrial Laser Scanning (TLS) – lot of work, not practical. May be better than LiDAR with large grid  
  Mobile Laser Scanning (MLS) OK but possible problems with vehicular access. May be better than LiDAR with large grid |
| Circular Slip                | Slope (either) | Semicircular cracking and lowering of slope section | X: 0.1-0.3  
  Y: 0.05-0.1  
  Z: 0.01-0.05 | RTK GPS Backpack mounted – Can combine with regular visual inspections. May not be accurate enough  
  Geo-referenced photography – accurate measurements difficult  
  LiDAR with 0.125m grid. Vegetation a possible problem. May miss some features. Slope differences may improve accuracy  
  Photogrammetry – needs considerable processing. Vegetation can cause problems.  
  Terrestrial Laser Scanning (TLS) – lot of work, not practical for a significant length  
  Mobile Laser Scanning (MLS) OK but possible problems with vehicular access |
| Slight                       |          |             | X: 0.3-1.0  
  Y: 0.1-0.5  
  Z: 0.05-0.2 | RTK GPS Backpack mounted – Can combine with regular visual inspections  
  RTK GPS Vehicle (grass cutter) mounted  
  LiDAR with 0.25m grid. Vegetation a possible problem  
  Geo-referenced photography – accurate measurements difficult  
  Photogrammetry – Needs considerable processing but can be very accurate  
  Terrestrial Laser Scanning (TLS) – lot of work, not practical. May be better than LiDAR with large grid  
  Mobile Laser Scanning (MLS) OK but possible problems with vehicular access |
| Minor                        |          |             | X: 1.0+  
  Y: 0.5+  
  Z: 0.2+ | RTK GPS Backpack mounted – Can combine with regular visual inspections  
  RTK GPS Vehicle (grass cutter) mounted  
  LiDAR with 0.5m grid. Vegetation a possible problem  
  Geo-referenced photography – accurate measurements difficult  
  Photogrammetry – needs considerable processing. Vegetation can cause problems.  
  Terrestrial Laser Scanning (TLS) – lot of work, not practical  
  Mobile Laser Scanning (MLS) OK but possible problems with vehicular access |
| Vermin Holes                 | Either slope | Holes in slope caused by vermin.  
  Slight = vole/rat size,  
  Minor="Rabbit size &  
  Major="Badger/Fox size | X:0.1-0.3  
  Y:0.1-0.5  
  Z:0.1-0.3 | Ground penetrating radar  
  Electrical Resistivity Tomography (ERT) |
| Minor                        |          |             |          |                     |

Work Package 4.2 Final Report   11 September 2012
<table>
<thead>
<tr>
<th>Visual Indicator / Asset type</th>
<th>Location</th>
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<th>Size (m)</th>
<th>Method and comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Major</td>
<td></td>
<td></td>
<td>X:0.3-0.6, Y:0.3-0.6, Z:0.3-0.6</td>
<td>Ground penetrating radar, Electrical Resistivity Tomography (ERT)</td>
</tr>
<tr>
<td>Slumping 3.3.3</td>
<td>Toe / Crest</td>
<td>Depression at toe or crest. If at toe, there may also be movement of slope above slump leading to a change in slope angle (SA)</td>
<td>X:0.1-0.2, Y:0.1-0.3, Z:0.02-0.05, SA: 1-5⁰</td>
<td>RTK GPS Backpack mounted – Can combine with regular visual inspections. May not be accurate enough, LiDAR with 0.125m grid. Vegetation a possible problem. May miss some features. Slope differences may improve accuracy. Geo-referenced photography – accurate measurements difficult. Photogrammetry – needs considerable processing. Vegetation can cause problems. Terrestrial Laser Scanning (TLS) – lot of work, not practical for a significant length. Mobile Laser Scanning (MLS) OK but possible problems with vehicular access.</td>
</tr>
<tr>
<td>Slight</td>
<td></td>
<td></td>
<td>X:0.2-1.0, Y:0.2-1.0, Z:0.05-0.4, SA: 5-10⁰</td>
<td>RTK GPS Backpack mounted – Can be combined with regular visual inspections, RTK GPS Vehicle (grass cutter) mounted, LiDAR with 0.25m grid. Vegetation a possible problem. Geo-referenced photography – accurate measurements difficult. Photogrammetry – Needs considerable processing but can be very accurate. Vegetation can cause problems. Terrestrial Laser Scanning (TLS) – lot of work, not practical. May be better than LiDAR with large grid. Mobile Laser Scanning (MLS) OK but possible problems with vehicular access. May be better than LiDAR with large grid. Motion sensors (e.g. accelerometers), Inclinometers, Time Domain Reflectometry, Detailed levelling.</td>
</tr>
<tr>
<td>Minor</td>
<td></td>
<td></td>
<td>X: 1.0+, Y: 1.0+, Z: 0.4+, SA: 10⁰</td>
<td>RTK GPS Backpack mounted – Can be combined with regular visual inspections, RTK GPS Vehicle (grass cutter) mounted, LiDAR with 0.5m grid. Vegetation a possible problem. Geo-referenced photography – accurate measurements difficult. Photogrammetry – needs considerable processing. Vegetation can cause problems. Motion sensors (e.g. accelerometers), Inclinometers, Time Domain Reflectometry, Terrestrial Laser Scanning (TLS) – lot of work, not practical. Mobile Laser Scanning (MLS) OK but possible problems with vehicular access.</td>
</tr>
<tr>
<td>Heaving 3.3.4</td>
<td>Toe / Crest</td>
<td>Uplift at toe or crest caused by geotechnical or hydraulic issues.</td>
<td>X:0.1-0.2, Y:0.1-0.3, Z:0.02-0.05</td>
<td>RTK GPS Backpack mounted – Can combine with regular visual inspections. May not be accurate enough, LiDAR with 0.125m grid. Vegetation a possible problem. May miss some features. Slope differences may improve accuracy. Geo-referenced photography – accurate measurements difficult.</td>
</tr>
</tbody>
</table>

3.3.4 Movement of toe / crest of slope. If at toe, may also be depression of toe / crest. May be slumping behind heave point.
### Visual Indicator / Asset type

<table>
<thead>
<tr>
<th>Location</th>
<th>Description</th>
<th>Size (m)</th>
<th>Method and comments</th>
</tr>
</thead>
</table>
| Minor    | X: 0.2-0.6  
Y: 0.2-0.6  
Z: 0.05-0.2 | RTK GPS Backpack mounted – Can be combined with regular visual inspections  
RTK GPS Vehicle (grass cutter) mounted  
LiDAR with 0.25m grid. Vegetation a possible problem  
Geo-referenced photography – accurate measurements difficult  
Photogrammetry – Needs considerable processing but can be very accurate. Vegetation can cause problems.  
Terrestrial Laser Scanning (TLS) – lot of work, not practical. May be better than LiDAR with large grid  
Mobile Laser Scanning (MLS) OK but possible problems with vehicular access  
Motion sensors (e.g. accelerometers)  
Inclinometers  
Time Domain Reflectometry  
Detailed levelling | |
| Major    | X: 0.5+  
Y: 0.5+  
Z: 0.2+ | RTK GPS Backpack mounted – Can be combined with regular visual inspections  
RTK GPS Vehicle (grass cutter) mounted  
LiDAR with 0.5m grid. Vegetation a possible problem  
Geo-referenced photography – accurate measurements difficult  
Photogrammetry – needs considerable processing. Vegetation can cause problems.  
Motion sensors (e.g. accelerometers)  
Inclinometers  
Time Domain Reflectometry  
Terrestrial Laser Scanning (TLS) – lot of work, not practical  
Mobile Laser Scanning (MLS) OK but possible problems with vehicular access | |

### Cracking & Fissuring

#### 3.3.2

| All | Presence of openings in bank and potential movement or erosion at crack or fissure points | Close-up photography and ‘standard’ measuring tools  
Photographic rulers  
Geo-referenced photography – for positioning and scope rather than detailed measurements | |

### Deterioration of surface protection

#### 3.3.6

| | Close-up photography and ‘standard’ measuring tools  
Photographic rulers  
Geo-referenced photography – for positioning and scope rather than detailed measurements  
Aerial photography  
Photogrammetry  
Near IR photogrammetry  
Multi- / Hyper-spectral imaging | |

### Large scale settlement or movement

#### 3.3.7

| | RTK GPS Backpack mounted – Can be combined with regular visual inspections  
RTK GPS Vehicle (grass cutter) mounted  
LiDAR with 0.5m grid. Vegetation a possible problem  
Geo-referenced photography – accurate measurements difficult  
Photogrammetry – needs considerable processing. Vegetation can cause problems. | |
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<th>Visual Indicator / Asset type</th>
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<th>Description</th>
<th>Size (m)</th>
<th>Method and comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Terrestrial Laser Scanning (TLS)</td>
<td>Lot of work, not practical</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mobile Laser Scanning (MLS)</td>
<td>OK but possible problems with vehicular access</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Motion sensors (e.g. accelerometers)</td>
<td>Inclinometers</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Time Domain Reflectometry</td>
<td>Terrestrial Laser Scanning (TLS)</td>
<td>Lot of work, not practical</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mobile Laser Scanning (MLS)</td>
<td>OK but possible problems with vehicular access</td>
<td></td>
<td></td>
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<tr>
<td>Ground Penetrating Radar</td>
<td>Gravity Gradiometry</td>
<td>Aeromagnetic Surveying</td>
<td>Seismic Reflection</td>
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<tr>
<td>Electrical Resistivity Tomography (ERT)</td>
<td>Electrical Resistivity Imaging (ERI)</td>
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<tr>
<td>Near IR photogrammetry</td>
<td>InSAR</td>
<td>ERT</td>
<td>Moisture sensors</td>
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<tr>
<td>GRAVITY WALLS Section 4</td>
<td>GRAVITY WALLS</td>
<td>GRAVITY WALLS</td>
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<tr>
<td>RTK GPS Backpack mounted</td>
<td>Can be combined with regular visual inspections. Only for earth behind?</td>
<td></td>
<td></td>
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</tr>
<tr>
<td>LiDAR with 0.125m grid.</td>
<td>Geo-referenced photography</td>
<td>Accurate measurements difficult</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Photogrammetry</td>
<td>Needs considerable processing but can be very accurate</td>
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<tr>
<td>Terrestrial Laser Scanning (TLS)</td>
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<td>Mobile Laser Scanning (MLS)</td>
<td>OK but possible problems with vehicular access. May be better than LiDAR with large grid</td>
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<tr>
<td>Motion sensors (e.g. accelerometers)</td>
<td>Inclinometers</td>
<td>Time Domain Reflectometry</td>
<td>Detailed levelling</td>
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</tr>
<tr>
<td>Aerial photography</td>
<td>Fixed Cameras</td>
<td>Surface mounted instrumentation (e.g. telltales)</td>
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**Work Package 4.2 Final Report**

11 September 2012

135
<table>
<thead>
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<th>Visual Indicator / Asset type</th>
<th>Location</th>
<th>Description</th>
<th>Size (m)</th>
<th>Method and comments</th>
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<tr>
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<td>RTK GPS Backpack mounted – Can be combined with regular visual inspections. Only for earth behind?</td>
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<tr>
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<td>Geo-referenced photography – accurate measurements difficult</td>
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<td>Photogrammetry – Needs considerable processing but can be very accurate</td>
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<td>Terrestrial Laser Scanning (TLS) – lot of work, not practical. May be better than LiDAR with large grid</td>
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<tr>
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<td>Mobile Laser Scanning (MLS) OK but possible problems with vehicular access. May be better than LiDAR with large grid</td>
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<td>Motion sensors (e.g. accelerometers)</td>
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<td>Inclinometers</td>
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<td>Time Domain Reflectometry</td>
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<td>Detailed levelling</td>
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<td>Aerial photography</td>
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<td>Fixed Cameras</td>
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<td>Surface mounted instrumentation (e.g. telltales)</td>
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<td>Backfill Washout 4.3</td>
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<td>Moisture sensors</td>
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<td>Ground Penetrating Radar</td>
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<td>Electrical Resistivity Tomography (ERT)</td>
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<td>Piping 4.3</td>
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<td>Near IR photogrammetry</td>
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<td>Moisture sensors</td>
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<tr>
<td>Deterioration of Material / Collapse 4.3</td>
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<td>Close-up photography and ‘standard’ measuring tools</td>
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<tr>
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<td>Photographic rulers</td>
</tr>
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<td>Geo-referenced photography – for positioning and scope rather than detailed measurements</td>
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<td>Subsurface condition 4.3</td>
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<td>Acoustic Emission Analysis</td>
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<td>X-Ray</td>
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<td>Ground Penetrating Radar (GPR)</td>
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<tr>
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<td></td>
<td></td>
<td>Sub-surface sensors (e.g. motion and moisture detection) – only for new-build. Consider power requirements</td>
</tr>
<tr>
<td>Visual Indicator / Asset type</td>
<td>Location</td>
<td>Description</td>
<td>Size (m)</td>
<td>Method and comments</td>
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<td>Tie / Anchor failure Section 5.1</td>
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<td>Geo-referenced photography for degree of corrosion – accurate measurements difficult Photogrammetry – Needs considerable processing but can be very accurate Terrestrial Laser Scanning (TLS) – lot of work, not practical. May be better than LiDAR with large grid Mobile Laser Scanning (MLS) OK but possible problems with vehicular access. May be better than LiDAR with large grid Inclinometers Time Domain Reflectometry Detailed levelling Aerial photography Fixed Cameras Surface mounted instrumentation (e.g. telltales) Accelerometers Tension gauges – for new-build</td>
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<td>Rotational Slip 5.1.1</td>
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<td>RTK GPS Backpack mounted – Can be combined with regular visual inspections. Only for earth behind? LiDAR with 0.125m grid. Geo-referenced photography – accurate measurements difficult Photogrammetry – Needs considerable processing but can be very accurate Terrestrial Laser Scanning (TLS) – lot of work, not practical. May be better than LiDAR with large grid Mobile Laser Scanning (MLS) OK but possible problems with vehicular access. May be better than LiDAR with large grid Motion sensors (e.g. accelerometers) Inclinometers Time Domain Reflectometry Detailed levelling Aerial photography Fixed Cameras Surface mounted instrumentation (e.g. telltales)</td>
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- Bore scope
- Pipe inspection robots
- Aerial (oblique) photography
- LIDAR
- RTK GPS (for beaches)
## G.4 Technology Summary

<table>
<thead>
<tr>
<th>Technology / Method</th>
<th>Asset Type</th>
<th>Problem</th>
<th>Comment</th>
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<td>Sheet Pile Wall</td>
<td>Overturning, Rotation about tie or toe</td>
<td>May miss slight problems even at this resolution</td>
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<td>Other</td>
<td>Uplift or sliding of slope protection, Beach topography, Salt marsh topography</td>
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<td>Asset Type</td>
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<td>Rotational slip</td>
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<td>Sheet Pile Wall</td>
<td>Overturning</td>
<td>May only detect major movement</td>
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<td>Rotation about tie or toe</td>
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<td>Quantitative assessment of surface topography for all asset types</td>
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<td>Accurate measurement difficult. Useful for assessing change</td>
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<td>Uplift or sliding of slope protection</td>
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<td>Subsurface condition appraisal</td>
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<td>Sheet Pile Walls</td>
<td>Seepage through wall</td>
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<td>Ultrasonic Testing (UT) / Pulsed Eddy Current (PEC)</td>
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<td>Corrosion testing (measuring thickness of sheet pile)</td>
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