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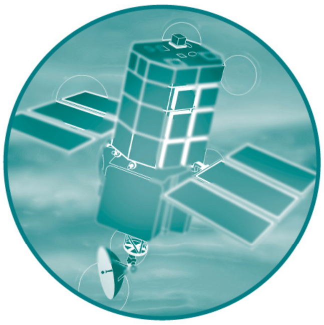

Engineering inspection techniques for flood defences using non-destructive testing

Report for O&M Concerted Action

R&D Technical Report W5A-059/2/TR

Use of Non-destructive Testing within Flood and Coastal Defence

R&D Technical Report W5A-059/2/TR

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Statement of Use
This report provides general information on non-visual methods of testing. It was produced under the R&D Concerted Action on O&M to screen for potential tests to compliment visual inspection of flood defences and provide a framework for their incorporation into present practice. It is available for general information to Flood Defence practitioners, but is not intended as an operational or management guide.

Keywords
Asset inspection, asset management, condition assessment, defects, geophysical investigation, non-destructive testing, flood defence, coastal defence

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EXECUTIVE SUMMARY

BACKGROUND

The Environment Agency (EA) has developed a structured procedure for obtaining and recording data on the National Sea and River Defences in England and Wales. The current system outlined in the Flood Defence Management Manual (FDMM) and supported by the Flood Defence Management System (FDMS) utilises a tool for visually assessing the condition of assets called the National Sea and River Defence Condition Assessment Manual. This provides a central inventory of the location and condition of component parts of flood defence systems. The current EA asset inspection system is principally visual. As part of its efforts to improve the condition assessment of its flood defence assets, the EA wishes to investigate the use of non-destructive testing within its asset condition assessment process.

This study is one of the quick-win initiatives carried out as part of the Flood and Coastal Defence the Operations and Maintenance (O&M) Concerted Action project, to assist in taking O&M business forward within a new/improved structure.

SCOPE OF STUDY

This study reviews the use of non-destructive testing to compliment the current visual inspection process with the view to improving the quality and effectiveness of the EA's asset condition assessment.

In order to gain an insight into current asset inspection philosophy, this study looks at the detailed asset data collection and inspection methods adopted by other large organisations with similar assets, and how non-destructive testing fits into their overall condition assessment process. In particular it gives a brief overview of the current approaches adopted by the UK dam, highways and rail industries.

OBSERVATIONS FROM SIMILAR ORGANISATIONS

A review of the management of assets within the road, dam and rail industries confirmed that non-visual inspection methods such as remote sensing and non-destructive testing are increasingly being incorporated within their condition assessment processes. These two techniques are increasingly being used as tools to assist with the asset condition assessment process. The emphasis seems to be on their targeted use to improve the quality of asset condition assessments. The decision to use non-destructive testing always arose from appropriately qualified and experienced individuals, working within a framework with clear roles and responsibilities. There is also great emphasis on pre-inspection planning, the use of competent staff for the inspections, the proper recording of assessments and the development of tools to assist with determining the need for, and the choice of, appropriate non-destructive testing methods.

CONCLUSIONS

Having reviewed the available systems and the requirements for effective adoption of non-destructive testing within the EA's asset condition assessment process, the following conclusions can be drawn:

Non-destructive testing can make a valuable contribution to the investigation of many problems that occur in a variety of structures including concrete, metals and embankments. Most of the EA's flood defence assets fall into this category.

Non-destructive testing offers significant advantages of speed, cost and lack of damage in comparison with test methods that require the removal of a sample for subsequent examination. Non-destructive testing can also allow the whole of a length of defence to be tested, rather than just one discrete point. The immediate availability of results could also be an important advantage.

The three ways in which non-destructive testing should be applied within an asset inspection framework are outlined below:

- Routine testing of some assets, where it has been identified following a risk assessment process that its exposure or loading conditions make it vulnerable to damage or deterioration which cannot be easily detected by visual inspection methods, and non-destructive testing is the most appropriate method. The frequency of inspection would depend on the expected rate of deterioration and associated flood risk.

- Further investigation of an asset, where a visual or other inspection has identified a possible defect or concern which cannot be properly assessed by visual methods and where a form of non-destructive testing is the most appropriate for providing further information for the assessment of asset condition.

- For establishing the extent of a problem and identifying areas where detailed intrusive investigations are needed.

Non-destructive testing should not be regarded as a complete diagnostic technique in itself, but as a potentially useful tool within a toolkit of methods for assessing the condition of an asset. It is not often that a single non-destructive testing technique will provide all the information that an inspector wishes to obtain. More commonly, it will provide additional evidence about a fault or problem that is already suspected. It can be useful for establishing the extent of a problem and identify areas where detailed intrusive investigations are needed.

To be an effective tool, non-destructive testing needs to be employed as part of an overall condition assessment framework. It is important that the relative benefits of its contribution in comparison to more conventional techniques are properly understood. The results from the non- destructive testing should be fed back into the assessment process and pooled with other inspection and testing results, and available management records.

Non-destructive testing methods are not suitable for the investigation of all defects. There will be cases where intrusive investigation or monitoring is required. This would occur where non-destructive testing methods are not appropriate, or where their results do not provide enough data for a conclusive assessment.

Before undertaking an investigation, the reasons for testing need to be clearly established before the detail of a test programme is planned. It is essential that there is agreement between the interested parties on the validity of the proposed testing procedures, the criteria for acceptance and the appointment of a person or laboratory to take responsibility for the testing and interpretation of the results.

It is widely recognised that skill and care by the operator is an important factor and that testing should be performed by adequately trained staff if worthwhile results are to be achieved. Whilst a few of the non-destructive testing techniques may be suitable for use by the inspector, more generally there will be a need to employ specialist firms or organisations. The inspector will need to have access to a database of asset management information. This includes design drawings, construction, historical performance, maintenance and previous inspection records.

RECOMMENDATIONS

It is recommended that the EA carry out the following actions:

- Carry out risk assessments of its assets to identify those at significant risk of damage from defects whose presence or extent cannot be easily identified by visual inspection. Appropriate methods of inspection (non-destructive or intrusive) should then be identified and a programme of routine testing developed within the overall asset inspection framework.

- Establish a system that ensures that adequately trained and experienced professionals, carry out the inspections and condition assessments of the EA's assets, supported by well-organised asset data. This system could involve a tiered level of expert involvement for efficient resources.

- Develop the use of non-destructive testing as an integral part of its asset condition assessment process to complement the existing visual inspection regime and other methods of inspection/investigations such as remote sensing, intrusive investigation and monitoring. These approaches should be incorporated into the forthcoming update of the EA's FDMM.

- Develop tools that map observed defects to symptoms/possible causes and appropriate methods for further testing. This will be a valuable tool to assist inspectors in deciding the likely causes of defects and advice on further testing and would facilitate the link from visual inspection to non-destructive or intrusive investigation methods.

CONTENTS

1. INTRODUCTION

The Environment Agency has developed a structured procedure for obtaining and recording data on the national sea and river defences and for the first time there is now in place a central inventory of the location and condition of component parts of flood defence systems. Standardised methods have been developed within the Flood Defence Management Manual (FDMM) for visual asset inspection, recording and reporting.

In order to gain an insight into current asset inspection philosophy, this study looks at the detailed asset data collection and inspection methods adopted by other large organisations with similar assets and how non-destructive testing fits into their overall condition assessment process. In particular it gives a brief overview of the current approaches adopted by the dam, highways and rail industries, and the European flood management sector.

This report provides a framework for improving the existing EA visual inspection process by considering the use of further testing to supplement the visual inspection regime and improve the quality and effectiveness of the EA's asset condition assessment. The common types of non-destructive testing techniques available and their various applications are outlined in Appendix A.

This study is one of the suite of quick-win initiatives carried out as part of the Flood and Coastal Defence the Operations and Maintenance (O&M) Concerted Action project, to assist in taking O&M business forward within a new/improved structure. Other relevant reports include:

- Investigation of "Fli-map" System for Flood Defence Asset Monitoring (Environment Agency, 2002a)
- Models for Reviewing Flood Defence Maintenance requirements (Environment Agency, 2002b)
- O&M Concerted Action Report (Environment Agency, 2002c).

2. ASSET INSPECTION METHODS

Current EA methods for data collection are based on walkover surveys. In recent years however, a number of cost effective asset inspection systems which could supplement visual inspection have become commercially available and are now being used by other organisations similar in stature to the EA.

Available asset inspection methods can be broadly described as one of the four below:

- Visual inspection
- Remote sensing
- Monitoring
- Non-destructive testing
- Intrusive investigation.

Visual inspection: This involves the physical presence of an inspector at a structure or defence to assess the condition of that asset by carrying out a walkover and general inspection of all accessible parts of the structure.

Remote sensing: This is the process of observing and obtaining information about an asset from a distance. The equipment for remote sensing could be mounted on the ground, moving vehicles, satellite, or on aircraft such as aeroplanes and helicopters. They generally utilise laser, photogrametry, videogrametry, electromagnetic radiation, radar or a combination of more than one of these techniques. Many of these innovative systems use specialised state of the art equipment to provide information that can be used to target visual inspection resources into risk areas. The speed of data capture makes some of these methods ideal for observing long stretches of linear assets such as flood embankments and sea defences.

Monitoring: This involves a systematic observation and recording of the condition of an asset and changes to that condition over a period of time. This will usually be carried out by frequent inspections or by the installation and monitoring of appropriate instrumentation in the area of concern.

Non-destructive testing: This is a method of obtaining information about internal characteristics of an asset from the surface of the asset. It does not involve any drilling or removal of any part of the asset. At the most, surface cleaning or pegging may be required.

Intrusive investigation: This is the process of obtaining further information about the internal characteristics of an asset by in-situ testing and by retrieving and testing samples from the asset. It normally involves physically reaching the internal part by excavation, boring, or probing methods. Within the scale of available methods, there are those with low levels of intrusion which will not affect the integrity of most flood defence structures. On the other hand, some methods are very intrusive and may not be suitable where continuous integrity is required.

Non-destructive testing methods are discussed in Section 3, with further information provided in Appendix A. Some of the available remote sensing techniques is summarised in Appendix B. Some of the available intrusive techniques, with relatively low levels of impact are summarised in Appendix C.

3. NON-DESTRUCTIVE TESTING

The three main types of material testing reviewed in this report are for concrete, metals and soils. The testing methods are discussed below in Sections 3.1, 3.2 and 3.3 respectively. The techniques used for the testing of the three types of materials are similar, but the methods of application are different. The methods outlined in this section should not be seen as an exhaustive list, as this area is currently undergoing significant development. Further details on each type of tests identified in this section are provided in Appendix A.

3.1 Non-destructive Testing of concrete

Non-destructive testing of concrete is usually related to an assessment of structural integrity or adequacy. It is used to check the quality of new structures as well as the condition of existing structures following a period of deterioration. Common non-destructive testing methods can be particularly useful for the following:

- Location and determination of the extent of cracks, delaminations, voids, honeycombing and similar defects.
- Determining the position, thickness or condition of reinforcement and cover.
- Determination of material uniformity, strength, stiffness and density.
- Confirming or locating suspected deterioration of materials from any number of factors.
- Assessing the durability of the elements of a structure
- Monitoring long term changes in material properties.
- Presence, location and condition of foundations.
- Presence of chlorides and sulphates.

Table 3.1 shows some of the available methods and uses of non-destructive testing within concrete structures:

Table 3.1 Non-destructive Testing of Concrete Structures

Method	Principal Uses
Electromagnetic cover meter	Indication of position, depth and size of reinforcement.
Resistivity measurement	Durability and likelihood of corrosion of reinforcement.
Half-cell potential measurements	Durability, location of reinforcement corrosion.
Radiometry	In- Situ density.
Radiography	Locating areas of variable compaction or voids.
Neutron moisture measurement	Assessing moisture content of surface zone.
Initial Surface absorption	Quality control for Pre-cast units.
Surface Permeability	Durability.
Maturity Measurements	Assessing Strength development.
Thermography	Detecting lamination and locating ingress of water and reinforcement.
Radar	Location of cracks and voids and determining thickness of slabs.
Strain measurements	Monitoring movement and assessing elasticity
Ultrasonic pulse velocity	Detection of cracking and honeycombing

Further detail on the methods in the above table is presented in Appendix A1.
Further detail about concrete testing in general is available in BS1881.

3.2 Non-destructive Testing of Metals

Non-destructive testing of metals is used for monitoring quality of items during manufacture, checking for fatigue or deterioration of items already in use (such as looking for cracks) and assessing defects where a decision needs to be made about the item's suitability to perform a task.

Commonly used testing techniques are used to assess the following properties:

- Identification of type and thickness of metal
- Surface defects, cracking and flaws.
- Internal corrosion
- Voids, disbonds and delaminations.
- Thickness of coating or cover.
- Length and integrity of piles
- Weld quality

Table 3.2 shows some of the available methods and uses of non-destructive testing within metallic structures:

Table 3.2 Non-destructive Testing of Metallic Structures

Method	**Main Use**
Ultrasonic Thickness Gauges	Determination of metal thickness
Ultrasonic Flaw Detectors	Detection of voids, disbonds and delaminations
Corrosion Mapping	Detection of internal corrosion
Magnetic Particle Inspection	Detection of surface defects
Coating Thickness gauges	Measuring coating thickness
Acoustic Emission Monitoring	Detecting flaws
Radiographic Inspection	Detecting flaws

Further detail on the methods in the above table is presented in Appendix A2.

3.3 Non-destructive Testing of Earth Embankments

Non-destructive testing of soils for civil engineering purposes is predominantly geophysical; some of these methods have successfully been adapted for use in embankment and similar structural investigations. It is important to recognise that in many cases, no one test will generate a complete picture; a number of different techniques may be required to generate a sufficiently high level of confidence.

A number of well established tests are available, which measure the following parameters:

- Density
- Location of voids, cavities and seepage
- Embankment or sub-soil movement
- Depth of a material, material layering or heterogeneity.

Table 3.3 shows some of the available methods and uses of non-destructive testing within soils:

Table 3.3 Non-destructive Testing of Earth Embankments or Sub-soil

Method	**Main Use**
Resistivity	Stratification and conductivity of embankment and sub-soil
Microgravity	Density, identification of voids or change in material.
Impulse Radar	Density, identification of voids or change in material.
Georadar	Sub-surface stratification, voids and material heterogeneity
Seiscope Microseismic monitoring	Movements and seepage

Further detail on the methods in the above table is presented in Appendix A3. Further details on testing on soils in general can also be found in BS 5930 and CIRIA C562.

4. ASSET INSPECTIONS IN SIMILAR INDUSTRIES

A review of the approaches to asset inspection and the role that non-destructive testing techniques play within three similar industries to flood and coastal defence was carried out. The industries chosen were Rail, highway and dam. The findings are summarised below. Further information about the individual industries is provided in Appendix D.

4.1 Summary of Inspection Methods within Similar Industries

The main elements common to the asset inspection methods employed by the three reviewed industries are summarised below:

- Use of adequately trained asset inspectors and condition assessment professionals.
- Increasing targeted use of non-destructive testing as part of routine inspection.

- Majority of use of non-destructive testing is to obtain more information where visual inspection is inconclusive, to further investigate concerns raised by visual or other form of inspection or to focus intrusive investigation onto appropriate areas.

- The link from visual inspection to non-destructive or other form of further testing is usually supported by tools such as pre-developed matrices, which map observed damage or concern to possible causes and appropriate methods for further investigation. These matrices are usually developed for different types of generic assets.

- Non-destructive testing is used alongside other inspection or testing or monitoring methods as an integral part of condition assessment.

  Where non-destructive testing is routinely used as part of a planned programme, this is usually identified by a risk assessment. Such testing will normally involve assets with high consequence of failure, where visual inspection or other condition assessment method is not practical, reliable or economical. Its main use however is to compliment visual inspection where a fault or problem is suspected within an overall asset condition assessment process.

  A review of the use of non-destructive testing within Europe shows that it is being used increasingly for the management of flood and coastal defence assets. In the Netherlands, the Manual for Safety Assessments of Flood Defences (currently being updated) allows for the use of non-destructive testing within a risk-based system for determining safety levels of defences. The system is based on flow charts, which allow gradually increasing levels of assessments from visual all the way to major intrusive investigations to be carried out, based on the complexity of each asset or defence system.

5. FRAMEWORK FOR USE OF NON-DESTRUCTIVE TESTING

The EA presently uses non-destructive testing very infrequently. A review of the EA's condition assessment procedures provided within the Flood Defence Management Manual (FDMM) shows that the condition assessment process is predominantly visual. Even when this does not provide a reliable result, there is no guidance on how further methods such as monitoring, non-destructive testing and intrusive investigations could be applied to assist with the overall condition assessment. In order to introduce non-destructive testing into the EA's condition assessment process, there is a need to recognise that it is only a part of an overall process that leads to reliable condition assessment.

An effective framework for asset inspection needs to start from the collation and use of information on the components that make up the asset as well as performance and risk information (see Figure 1). The appropriate method and frequency of the routine assessment of an asset needs to be based on the type of assets involved, their risk of failure and local issues. The inspection process could involve a high level method such as remote sensing if appropriate, followed by visual inspection. Where these methods are unable to provide the level of reliability required for the risks involved, non-destructive testing or intrusive investigation if appropriate could be considered as part of the routine inspection/testing programme.

If routine inspection/testing, does not provide a reliable assessment, or concerns are identified which require further information to provide an assessment, further testing should be carried out (depending on the level of uncertainty and risks involved). Pre-developed tools that assist in mapping problems to possible causes and appropriate investigation methods will assist the process of assessing what further investigation(s) is appropriate. One of such investigations could be a form of non-destructive testing. The results of such further testing should be fed back into the assessment process and considered with the other information on performance, inspection and testing to provide an assessment of the condition of the asset. Technically competent professionals should always be involved in confirming the need for further testing as well as determining the appropriate testing method(s).

The framework described above is illustrated in Figure 1. Judgement and experience are important parts of any condition assessment. Appropriately trained and experienced engineers need to be involved with the inspection and assessment process and in the decision on need for further testing. If further testing is required, this is usually a specialist area.

The levels of expertise required for the various stages differ. While the routine inspections could be carried out by adequately trained local EA operations staff, the level of training and experience required for interpreting the observations, assessing the condition and determining the need for further testing is higher. Significant understanding of asset behaviour and deterioration over time and the effect of these on current state and future performance are critical at this stage. If a need is then determined that a particular type of further works (e.g. non-destructive testing is required, specialist advise should then be sought on the details of the testing. Most of the non-destructive testing methods require the use of specialists either for the field work or interpretation. The framework in Figure 1 will need to be developed with the required expertise in mind.

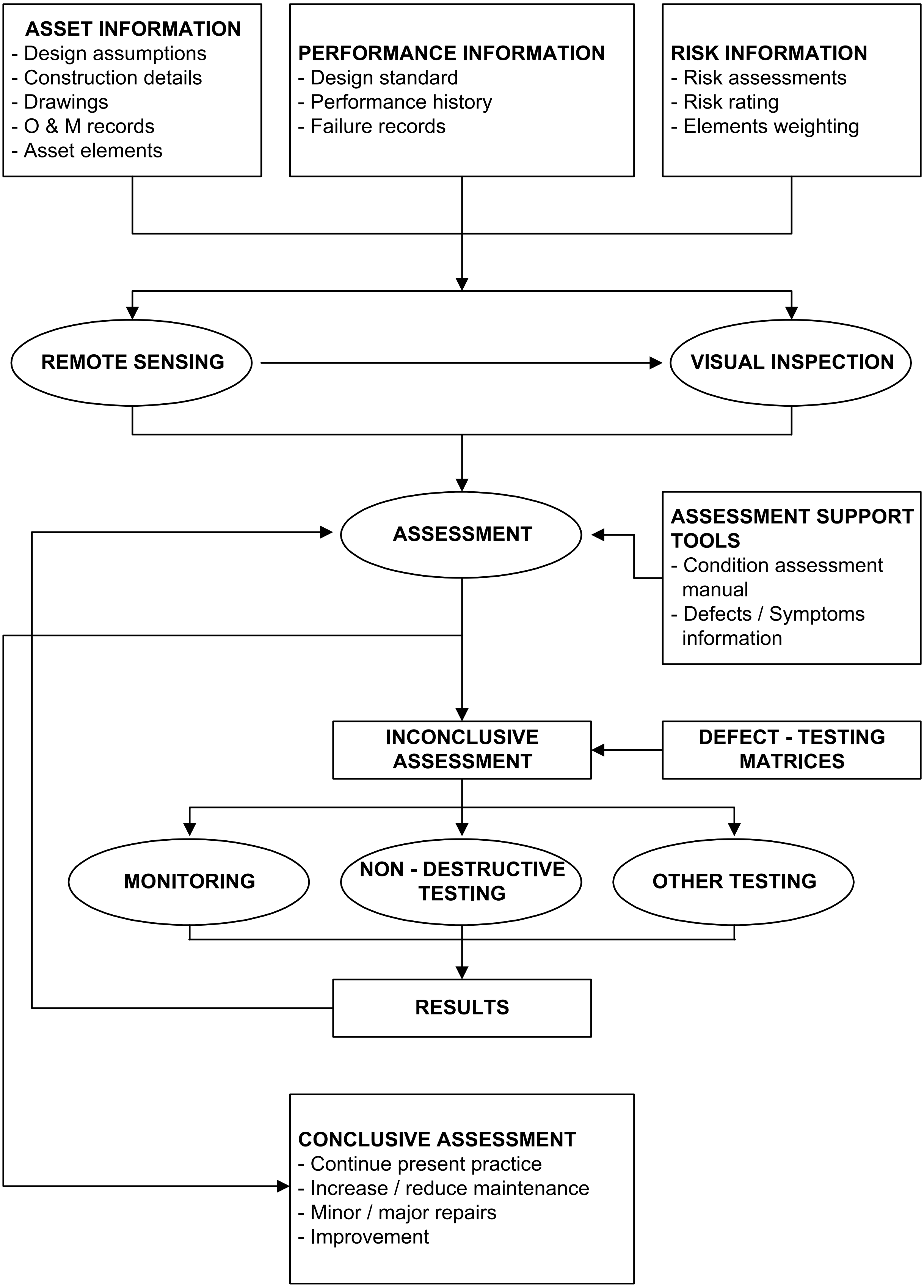

Figure 1 Proposed Asset Inspection Framework

6. CONCLUSIONS

Having reviewed the available systems and the adoption of non-destructive testing within the EA's asset condition assessment process, the following conclusions can be drawn:

Non-destructive testing can make a valuable contribution to the investigation of many problems that occur in a variety of structures including concrete, metals and embankments. Most of the EA's flood defence assets fall into this category.

Non-destructive testing offers significant advantages of speed, cost and lack of damage in comparison with test methods that require the removal of a sample for subsequent examination. Non-destructive testing can also allow the whole of a length of defence to be tested, rather than just one discrete point. The immediate availability of results could also be an important advantage.

The two ways within which non-destructive testing should be applied within an asset inspection framework are outlined below:

- Routine testing of some assets, where it has been identified following a risk assessment process that its exposure or loading conditions make it vulnerable to damage or deterioration which cannot be easily detected by visual inspection methods, and non-destructive testing is the most appropriate method. The frequency of inspection would depend on the expected rate of deterioration and associated flood risk.

- Further investigation of an asset, where a visual or other inspection has identified a possible defect or concern which cannot be properly assessed by visual methods and where a form of non-destructive testing is the most appropriate for providing further information for the assessment of asset condition.

- For establishing the extent of a problem and identifying areas where detailed intrusive investigations are needed.

Non-destructive testing should not be regarded as a complete diagnostic technique in itself. It is not often that a single non-destructive testing technique will provide all the information that an inspector wishes to obtain. More commonly, it will provide additional evidence about a fault or problem that is already suspected. It can be useful for establishing the extent of a problem and identify areas where detailed intrusive investigations are needed.

To be an effective tool, it needs to be employed as part of an overall condition assessment framework. The results from the testing should be fed back into the assessment process and pooled with other visual and other records to improve assessments.

Non-destructive testing methods are not suitable for the investigation of all defects. The decision to use them should be always be taken by an appropriately qualified individual.

Before undertaking an investigation, the reasons for testing need to be clearly established before the detail of a test programme is planned. It is essential that there is agreement between the interested parties on the validity of the proposed testing procedures, the criteria for acceptance and the appointment of a person or laboratory to take responsibility for the testing and interpretation of the results.

It is widely recognised that skill and care by the operator is an important factor and that testing should be performed by adequately trained staff if worthwhile results are to be achieved. Whilst a few of the non-destructive testing techniques may be suitable for use by the inspector, more generally there will be a need to employ specialist firms or organisations.

7. RECOMMENDATIONS

It is recommended that the EA carry out the following actions:

- Carry out risk assessments of its assets to identify those at significant risk of damage from defects whose presence or extent cannot be easily identified by visual inspection. Appropriate methods of inspection (non-destructive or intrusive) should then be identified and a programme of routine testing developed within the overall asset inspection framework.

- Establish a system that ensures that adequately trained and experienced professionals, carry out the inspections and condition assessments of the EA's assets, supported by well-organised asset data. This system could involve a tiered level of expert involvement for efficient resources.

- Develop the use of non-destructive testing as an integral part of its asset condition assessment process to complement the existing visual inspection regime.

- Develop tools that map observed defects to symptoms/possible causes and appropriate methods for further testing. This will be a valuable tool for inspectors in deciding the likely causes of defects and advice on further testing and would facilitate the link from visual inspection to non-destructive or intrusive investigation methods.

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APPENDIX A

NON-DESTRUCTIVE TESTING METHODS

APPENDIX A – NON-DESTRUCTIVE TESTING METHODS

A1 Testing of Concrete

Non-destructive testing of concrete is usually related to an assessment of structural integrity or adequacy. It is used to check the quality of new structures as well as the condition of existing structures following a period of deterioration.

The table below shows some of the available methods and uses of non-destructive testing within concrete structures:

Method	**Principal Uses**
Electromagnetic cover meter	Indication of position, depth and size of reinforcement.
Resistivity measurement	Durability and likelihood of corrosion of reinforcement.
Half-cell potential measurements	Durability, location of reinforcement corrosion.
Radiometry	In- Situ density.
Radiography	Locating areas of variable compaction or voids.
Neutron Probe moisture measurement	Assessing moisture content of surface zone.
Initial Surface absorption	Quality control for Pre-cast units.
Surface Permeability	Durability.
Maturity Measurements	Assessing Strength development.
Thermography	Detecting lamination and locating ingress of water and reinforcement.
Radar	Location of cracks and voids and determining thickness of slabs.
Strain measurements	Monitoring movement and assessing elasticity
Ultrasonic pulse velocity	Detection of cracking and honeycombing

Electromagnetic cover measurement

The equipment is calibrated to indicate the position, depth and size of reinforcement bars. Various portable instruments are commercially available based upon change of an electromagnetic field caused by steel embedded in the concrete. The equipment is generally inexpensive, lightweight and self contained.

Resistivity measurements

In situ measurements of electrolytic resistivity of concrete is measured by installing a series of probes in a straight line on or just below the concrete surface. An electrical current is passed and the resistivity of the concrete is calculated. Experienced investigators have used this method to assess or monitor the durability of concrete exposed to severe environments and in some cases, the likelihood of corrosion of embedded reinforcement may be predicted.

Half-cell potential measurements

This simple equipment which uses a half-cell placed on the concrete surface produces an isopotential contour map which can be used for assessment of the durability of reinforced concrete members where reinforcement corrosion is suspected. Often used in locations of high reinforcement corrosion risk such as in marine structures, bridge decks and abutments. Used in conjunction with other tests, it is a useful for investigating concrete contamination by salts.

Radiometry

A narrow beam of gamma rays is directed into the concrete and the intensity of the radiation emerging is measured by means of a Geiger counter or a scintillation detector. This method provides a method of assessing in situ density and permits examination of a concrete member. Portable equipment incorporating a microprocessor is commercially available.

Radiography

A 'photograph' of the Interior of the concrete is obtained from which variations of density can be identified. This is produced on a suitable film held against the rear face of the concrete, while a beam of gamma rays or high energy X-rays is directed at the front face. The presence of high-density materials, such as reinforcement, or low density areas caused by voids will produce light and dark areas on the film. The method is particularly valuable for locating areas of variable compaction or of voids in concrete.

Neutron Probe moisture measurement

The principle application of this method is the estimation of the moisture content of the surface zone. The energy of fast or high-energy neutrons is rapidly reduced by the presence of low-energy neutrons such as the hydrogen contained in water. Portable forms of the equipment are commercially available incorporating a microprocessor capable of providing direct readings.

Initial Surface absorption

Initial surface absorption involves measurement of the rate of flow of water per unit area into a concrete surface subjected to a constant applied head. The equipment consists of a cap that is clamped and sealed to the concrete surface, with an inlet connected to a reservoir and an outlet connected to an horizontal calibrated capillary tube and scale. Measurements are made of the movement of water in the capillary tube over a fixed period of time following closure of a tap between the cap and the reservoir. The principal use is as a quality control test for pre-cast units when dry and in assessing potential durability.

Surface Permeability

Several methods are available which permit an assessment of the permeability of concrete in the surface zone to water, air, carbon dioxide or other gasses under pressure. These methods provide practical ways of assessing the permeability of surface zone concrete under in situ conditions. This information is particularly valuable as an indicator of potential durability.

Maturity measurements

The measurement of maturity is a simple technique which takes account of the temperature history within the concrete during hydration and is used to ascertain strength development for a particular concrete mix. Disposable meters based on temperature dependent chemical reaction and electrically operated meters using temporary sensors are available.

Thermography

Thermography involves the recording of surface differentials on a concrete member undergoing heating or cooling. Three types of equipment are available, a quantitative temperature measuring gun, a qualitative thermal imager and a scanner and cathode ray monitor. The principal uses are for detecting of lamination and for locating ingress of water and of reinforcement.

Radar

A surface-penetrating radar system may be used to examine the refractions of short duration pulses from interfaces between materials with different dielectric constants lying below the surface. The principal applications are in the location of voids, cracks, delamination and reinforcing bars. The thickness of slabs and location of voids beneath ground slabs can also be determined.

Strain measurements

Strain gauges can be used to measure apparent strain caused by crack propagation, thermal changes etc. The principal applications include monitoring of movement, assessing the elasticity of structural members and in load testing.

Ultrasonic Pulse velocity measurement

This equipment measures the transit time of a pulse between transducers placed on the surface of a body of concrete and can be used to determine concrete uniformity and for detection of cracking and honeycombing.

A2 Testing of Metals

Non-destructive testing of metals is used for monitoring quality of items during manufacture, checking for fatigue or deterioration of items already in use (such as looking for cracks) and assessing defects where a decision needs to be made about the item's suitability to perform a task.

The Table below shows some of the available methods and uses of non-destructive testing within metallic structures:

Method	**Main Use**
Ultrasonic Thickness Gauges	Determination of metal thickness
Ultrasonic Flaw Detectors	Detection of voids, disbonds and delaminations
Corrosion Mapping	Detection of internal corrosion
Magnetic Particle Inspection	Detection of surface defects
Coating Thickness gauges	Measuring coating thickness
Accoustic Emission Monitoring	Detecting flaws
Radiographic Inspection	Detecting flaws

Ultrasonic Thickness Gauges

A Number of types of handheld precision gauges are commercially available which measure material thickness. They can be used to determine metal thickness under a coating such as paint and are accurate up to 0.01mm.

Ultrasonic Flaw detectors

Hand held flaw detectors are used for the critical examination of composite and structural members to indicate voids, disbonds and delaminations.

Guided wave ultrasonic inspection uses guided, long range, ultrasonic waves for the examination of lengths of symmetrical components such as rails or pipes. The ultrasonic waves propagate through many metres of the component, and can detect buried defects such as corrosion and cross sectional cracking.

Corrosion Mapping

Corrosion Mapping uses eddy current arrays or ultrasound phased arrays to detect and measure internal corrosion. Inexpensive portable units are available which allow detection and quantification of unseen potential defects before they become problems.

Magnetic Particle Inspection

Magnetic Particle Inspection can be used to find defects on the surface or near the surface in materials that can be magnetised. The method uses the application of fine iron to the surface of the item following temporary magnetism. The principle is that the fine iron particles will form along the lines of the magnetic force from the magnet. These lines will be distorted by flaws and thus revealing their presence.

Coating Thickness Gauges

A number of coating thickness gauges are available for measuring thicknesses of coatings from paint to hot dip galvanising on steel.

Acoustic Emission Monitoring

Acoustic emission monitoring is used to detect flaws which are not able to be seen with the naked eye. A microphone is attached to the item being tested and the sounds of the item are analysed while the item is placed under load or into use. The analysis is performed using computer-based equipment.

The sounds that are generated include noise from friction, crack growth, leakage and changes in material, which are inaudible to the human ear, and so can detect miniscule changes.

Radiographic Inspection

Radiographic Inspection uses X-Rays or Gamma rays to examine a component or surface. The X-Rays are produced using high voltage X-ray machines and gamma rays are produced using radioactive isotopes. The rays are directed at the item to be tested so that they pass through it – the resulting image is captured on film. The film is then processed and the result is a series of grey shades which will show any defects (as the ray passes through them differently to the surrounding material).

A3 Testing of Soils

The non-destructive testing of soils for civil engineering purposes is predominantly geophysical; some of these methods have successfully been adapted for use in embankment and similar structural investigations. It is important to recognise that in many cases, no one test will generate a complete picture; a number of different techniques may be required to generate a sufficiently high level of confidence.

The Table below shows some of the available methods and uses of non-destructive testing within soils:

Method	**Main Use**
Resistivity	Stratification and conductivity of embankment and sub-soil
Microgravity	Density, identification of voids or change in material.
Impulse Radar	Density, identification of voids or change in material.
Georadar	Sub-surface stratification, voids and material heterogeneity
Seiscope Microseismic monitoring	Movements and seepage

Resistivity

Resistivity measurements assess the conductivity of the ground. A resistivity investigation is usually achieved by driving two electrodes into the ground and measuring the currents passing between them. By varying the spacing and geometrical arrangement of the stakes, an electrical "drilling" or "trench" can be synthesised to identify major changes in stratigraphic ground conductivity.

Microgravity

Microgravity measures small perturbations in the earth's gravitational field. These may be caused for example by voids or dense structures buried in the ground or changes in the relative thickness of two layers of material of different density. This method identifies local changes in density within the near surface as a contrast in the local gravitational field. For the method to work successfully to a depth of about 5m, it is important that access is available to approximately 10m of either side of any possible void location.

This method is commonly used for finding areas of low density as indicators of possible voiding. A grid is usually established over the upper surface as a series of stations at about 2.5m centres.

Impulse Radar

Impulse radar works by inducing an electromagnetic pulse of energy into the structure under investigation and measuring the changes in wave velocity as the pulse passes from one material type to another. This change causes energy to be reflected at the boundary between material types so that when it reaches a receiver a record of the interface is produced.

The system utilises the principle that radio waves travel at different velocities through different materials; the velocity is dependent on the electrical characteristics of each material. Impulse radar records the change in that electrical difference and this can be used to map areas of voiding and low density. However, materials of highly reflective characteristics such as metals prevent the penetration of radio energy. Similarly, those that readily absorb electromagnetic radiation (such as wet clay) obscure the resolution of features within or beneath such as voiding.

Georadar

Georadar uses radar technology to obtain a continuous profile of the subsurface and is of great interest in embankment dam safety as it allows access to quality information on:

- Water table level.
- Anomalies or heterogeneities in the material.
- Stratigraphic profiles.
- Voids and cavities.
- Material layering

The method can be applied following the construction of an embankment and over time to follow evolution or degradation.

Seiscope Microseismic Monitoring

This system, used in embankment dam monitoring, records signals generated by the embankment itself and its geological environment. The system constantly monitors the embankment and its surroundings, by sensing through geophones and accelerometers strategically located for acoustic or seismic signal.

The origin of these signals can be geological movements, stress releases in the embankment, progression of fracture networks and seepage. Each of these phenomena has its distinguishable signature. By mathematical modelling, the epicentres can be located and mapped.

APPENDIX B

REMOTE SENSING METHODS

APPENDIX B – REMOTE SENSING METHODS

Laser Induced Direction & Ranging (LIDAR)

Airborne LIDAR systems emit rapid pulses of light to precisely measure distances from a sensor mounted in a port opening on the bottom of an aircraft's fuselage to targets on the ground. The technique produces a digital terrain model with a height accuracy of 100 to 150mm and a horizontal resolution of 1 to 4m. LIDAR can quickly generate a large number of terrain data points and commercial systems are available with typical data capture rates of 100 km^2 /hr. Typical applications have been floodplain mapping and mapping of the coastal zone.

Scanning Hydrographic Operational Airborne Lidar Survey (SHOALS)

SHOALS is a system which simultaneously collects bathymetry and adjacent topography. The system uses a scanning pulsing laser to deliver light at two frequencies: blue-green and infrared. While the infrared pulse provides a direct ranging of the water surface, the blue-green pulse penetrates the water column to provide direct ranging of the sea bottom. Two or three-dimensional positioning of the SHOALS aircraft is from differential GPS or Kinematic GPS respectively.

In addition to depth measurements, the SHOALS system simultaneously measures adjacent shoreline topography by directly ranging the terrain with it's blue-green laser. SHOALS can collect individual soundings every eight meters and surveys at a rate of 400 soundings per second, or 25 km^2 per hour. The accuracy of the soundings is given as ± 3m in the horizontal and ± 150mm in the vertical.

The SHOALS system has been used in the USA to fully map near-shore regions from the shoreline to the 30m contour.

Fast Laser Imaging Mapping Airborne Platform (FLIMAP)

FLIMAP is a proprietary helicopter mounted laser altimetry system co-ordinated by 6 GPS satellites and complemented by video cameras, which provide high definition and high-resolution output.

The system is calibrated using ground base stations at 25km centres and gives a level accuracy of ± 75mm coupled with a production rate of 70 Km/h. Data is usually presented in conjunction with an Ordnance survey digital backcloth.

The main applications of FLIMAP to date have been in Rail Asset Inventory, embankment monitoring and for populating Highway Authority's GIS systems. The technology combines high definition and still images which can be integrated into existing GIS applications. It was recently tested on flood defences (Environment Agency, 2002b).

Videogrammetrical Acquisition

A Videogrammetrical survey system uses robotic stations and detail and panoramic cameras. The system produces a total ‘ As-Built’ 3D survey record with the ability to extract co-ordinates of all features which can be used as a benchmark for future condition monitoring.

Videogrammetrical survey has been used to record rail & road tunnels, bridges, viaducts and other structures.

Asset Mapping

Asset mapping has recently been used to map highways and rail assets. The system is based on a vehicle mounted video system and GPS and can position an asset to within 1m on an OS backcloth.

Hazardous Environment Data Acquisition (HEDA)

HEDA provides the ability to remotely collect data in areas of restricted access or hazard. Using traditional survey techniques in conjunction with state of the art technology it enables gathering of information from a position of safety. Under ideal conditions the accuracy is ± 3mm. Applications have mainly been in the rail Industry, to minimise possession times and on structures to alleviate the need for platform access.

Aerial mapping

Aerial Mapping using stereo photography provides an efficient and cost effective data collection system, enabling topographic information to be systematically captured in 3 dimensions.

Orthophoto Mapping

Orthophoto maps are scale corrected aerial photographs which have been seamlessly joined together to produce a map which may be output as a printed photographic map or in digital form. Orthophotos take account of and correct for the terrain ensuring that each pixel is in it’s correct geographical position.

A lower cost alternative is digital photo mosaics whereby each aerial photograph is stretched to ‘fit’ the surrounding photography.

Satellite Remote Sensing

Satellite remote sensors record the intensity of electromagnetic radiation (sunlight) reflected from the earth at different wavelengths. They rely on the fact that particular features reflect light differentially in different wavelengths.

The satellite detectors measure the intensity of the reflected energy and record it as a number between 0 and 255. The numbers recorded for different satellite bands are displayed in green, red and blue.

Satellite remote sensing has a number of advantages over aerial photography, namely:

- The acquisition of infrared reflectance better enables identification and assessment of features.
- Images can be acquired on a regular basis enabling access to current and archived data.
- Images can be reproduced in photographic or digital form. Cheap and user friendly software is now available to view and analyse images on PC's.

Satellite remote sensing has been used to monitor coastal landscape change as well as monitoring protected areas, urbanisation topographical changes and in soil erosion mapping.

APPENDIX C

INTRUSIVE INVESTIGATION WITH LOW LEVELS OF DISTURBANCE

APPENDIX C INTRUSIVE INVESTGATION TECHNIQUES WITH LOW LEVELS OF DISTURBANCE

In addition to the techniques outlined in the earlier appendices, some intrusive techniques are available which are considered as relevant to this study due to their relatively low levels of disturbance. While they may involve some disturbance of the asset or removal of some particles, they do not usually affect the integrity of the defences. These are seen as the next steps from non-destructive testing methods. Some examples are described below:

C1 Testing of Concrete

Method	Principal Uses
Dynamic Response	Structural Integrity, identification of defects.
Surface Hardness	Determination of uniformity and in-situ strength.
Screed test	Assessment of durability and quality of floor screeds.
Internal Fracture	Assessment of strength.
Pull-out test	Assessment of strength.
Pull-off test	Assessing strength
Penetration resistance	Assessing strength
Acoustic emission	Crack monitoring

Dynamic response techniques

Several techniques are available that measure the response of a structural member to an imposed load. The simplest of these is the pulse echo method where reflected shock waves resulting from a single hammer blow are monitored using a hand held accelerometer coupled to a signal processor. Uses include assessment of structural integrity and remaining service life and identification of defects.

Surface hardness

A number of hand held spring loaded steel rebound hammers are available to suit a variety of concrete types. This method can be used to determine concrete uniformity, monitor strength development and determine in situ strength.

Screed test

Measurement of the surface indentation caused by a defined number of repeated controlled hammer blows may be empirically related to the soundness of the screed. The principal application is the assessment of durability and quality of floor screeds.

Internal Fracture

A 6mm diameter expanding wedge anchor bolt is fixed into a drilled hole in the concrete surface and the peak force is recorded when the bolt is pulled against a reaction tripod on the surface. This method is a simple and cheap method of estimating the strength of in-situ concrete.

Pull-out test

Pull-out tests involve measurement of the force required to pull a metal insert from within the concrete against a reaction ring. The insert may be cast in the concrete or may be positioned in an under-reamed groove from a drilled hole. Cast-in inserts are used for quality control or strength monitoring purposes and inserts fixed into drilled holes used for in situ strength estimation.

Pull-Off test

The Pull-off test uses a circular disc glued to the surface of the concrete with an epoxy or polyester resin. The force required to pull this from the surface together with an attached layer of concrete using simple hand operated loading equipment is measured. The principal applications are quality control, long term monitoring and in situ strength assessment.

Penetration resistance

Penetration resistance involves firing a steel bolt (probe) into the surface of the concrete. A standardised charge is used and the depth of penetration is measured. This method can be used to estimate the strength of in situ concrete

Acoustic emission

This method involves the detection of small amplitude stress waves propagated throughout a material as local crushing or microcracking occurs. These are detected using transducers connected to electronic processing equipment. The method can be used to monitor the initiation, origin and development of internal cracking and local breakdown during load testing, and to provide a warning of impending failure.

C2 Testing of Metals

Method	Main Use
Liquid Dye Penetrant	Detection of surface defects

Liquid Dye Penetrant

This method is used to detect surface breakage and can be used on any material. The item to be tested is thoroughly cleaned and then coated with a liquid which is drawn into the surface. After a period of time has elapsed to allow the liquid to be drawn into any cracks, the excess liquid is removed and a second liquid, which acts as a developer is applied. The developer draws the penetrant from the crack, making the crack visible.

Some penetrants are coloured and require good fluorescent white light to be seen, while others require illumination by ultraviolet light.

C3 Testing of Soils

C3.1 Density of Soil

These tests are used to determine the in-situ density of soil.

Sand Replacement Method (small pouring cylinder method)

This method is used to determine the in-situ density of natural or compacted fine and medium grained soils. The method uses a 115mm diameter sand pouring cylinder in conjunction with replacement sand.

Sand Replacement Method (large pouring cylinder method)

This method is similar to that described above and is used to determine the in-situ density of fine, medium and coarse grained soils.

Water Replacement Method

This method is used to determine the in situ density of natural or compacted coarse-grained soil. The method uses a circular density ring on the ground surface and a flexible plastic sheet to retain water to determine the volume of an excavated hole.

Core Cutter Method

The core cutter method is used to determine the in-situ density of natural or compacted soil using a cylindrical steel core cutter rammed into the surface of the soil.

Nuclear Gauges

Nuclear gauges are commercially available and are suitable for fine, medium and coarse grained soils. The equipment used utilises radioactive materials emitting ionizing radiation.

C3.2 Vertical deformation and strength

These tests are used to investigate the strength and load settlement characteristics of soil

Plate Loading Test.

The plate loading test can be used to measure vertical deformation and strength characteristics of soil in-situ by assessing the force and amount of penetration with time when a rigid plate is made to penetrate the soil.

The main uses are in evaluating the ultimate bearing capacity, shear strength and deformation parameters of soil beneath the plate.

The method may be carried out at the ground surface, in pits or trenches and in the bottom of a borehole.

Shallow Pad Maintained Load Test

In this test the settlement characteristics of the soil are determined using a constant load applied to the ground for a period of several weeks through a pad located at shallow depth. The test is suitable for estimating the settlement caused by structures with lightly loaded shallow foundations built on filled ground and on some types of soft natural soils.

Determination of the in-situ California Bearing Ratio (CBR)

The CBR is defined in the form of a percentage, as the ratio of the force exerted on a specified material compacted and confined in a given manner.

The CBR of a soil in-situ is determined by causing a cylindrical plunger to penetrate the soil at a given rate and comparing the relationship between force and penetration into the soil to that for a standard material.

Vane Test

This test is used to determine the in-situ shear strength of soils using a vane of cruciform section, which is subjected to a torque of sufficient magnitude to shear the soil. The test is suitable for very soft to firm intact saturated cohesive soils.

C3.3 Corrosivity tests

These tests are used to determine the likelihood of underground corrosion of buried metal structures.

Redox potential of soil

This method determines the redox potential (reduction/oxidation) of soil by measuring the electro-chemical potential between a platinum electrode and a saturated calomel reference electrode.

The test is used to indicate the likelihood of microbial corrosion of metals by sulphate reducing bacteria, which can proliferate in anaerobic conditions.

APPENDIX D

USE OF NON-DESTRUCTIVE TESTING WITHIN ASSET MANAGEMENT IN SIMILAR INDUSTRIES

This appendix presents a summary of the asset management procedures within the UK dam, highway and rail industries, and the way non-destructive industry is used within their overall asset inspection systems.

D1 Dam Industry

D1.1 Introduction

Around 2500 reservoirs within the U.K. come within the ambit of the Reservoirs Act 1975. Of these, about 80% are embankment dams, with the remainder being concrete dams and service reservoirs. The ages of these dams vary between a few years and about 900 years; 70% of the dams were built prior to 1900.

The Act requires that the inspection of reservoirs is the responsibility of “qualified civil engineers”. These engineers outlined within the act are the construction Engineer, “the Inspecting Engineer” and “the Supervising Engineer”, each with clear definition of roles and responsibilities.

Any published inspection guidelines are non-prescriptive and are only advisory. This practice is intended to ensure that the inspection process is risk based and cost effective. The guidelines cover the inspection process. This includes the frequency of inspection, pre-inspection activities, actual inspection process, inspection recommendations and reporting.

D1.2 Inspection Process

The inspection is primarily visual, with the designated engineer physically assessing all accessible parts of the dam and its structures. All defects, such as cracks, deformities, leaks and overtopping are noted and any required remedial actions outlined.

Observations of defects such as settlement, apparent instability, seepage and leakage flows are recorded. The risk of a defect leading to catastrophic failure is also analysed. All existing monitoring points are checked and the data on the instrumentation noted. Instrumentation such as piezometers, settlement gauges and water level indicators are in common use and are often installed during construction of the dam. More recently, non-destructive techniques such as Georadar and Seiscope Microseismic monitoring techniques are being employed. These are discussed further in Appendix A.

The use of non-destructive testing techniques normally occurs as a result of requests either by the construction engineer following the construction or improvement of a reservoir or by the inspecting or supervising engineer following a period of supervision or inspection. The reasons for testing, the frequency and the required analysis of the results will be clearly stated as part of the report requesting the testing. The results are normally considered along with other observations, tests and historic information to provide an assessment of the condition of the assets or to make further recommendations. Non-destructive testing is treated as a means to an end and not an end in itself.

D2 Highways Agency

D2.1 Introduction

In England, The Highways Agency sets out the requirements for the inspection of Highways structures and completion of inspection reporting forms. The requirements include the frequency of inspection, pre-inspection activities, actual inspection process, inspection recommendations and reporting. The majority of the Highway Agency structures are bridges (over 1500).

Inspections are carried out in order to safeguard the public and to enable the maintenance of the stock of to be planned on a national basis in a systematic manner. Inspection is also seen as having a valuable part to play in providing data for assessing the load carrying capacity of a structure and in providing a feedback of information into design and construction practices. It is widely recognised that staff involved in inspections should be adequately trained if a high standard of inspection is to be achieved. The Highways Agency also has clearly identified roles and responsibilities.

D2.2 Inspection Process

Four main types of Inspection of Highways Assets are undertaken. These are superficial inspection, general inspection, principal inspection and special inspections. The first three types of inspections are routinely carried out within maximum intervals, while the special inspection is carried out as required when a closer examination of a particular area or defect is required. An increasing number of special inspections are carried out using non-destructive testing methods.

Examples of situations where special inspections are carried out include the following:

- To investigate a specific problem either found during inspection or already discovered on other similar structures.
- For structures which have weight restrictions, other forms of restriction or have been strengthened or carried an abnormal load.
- In areas of mineral extraction when subsidence occurs or if observed settlement is greater than that allowed for in the design.
- To a river bridge after flooding or when there is a possibility that scour has occurred (in which case a further underwater inspection is carried out)
- In accordance with statutory requirements for Mechanical, Electrical and Structural elements.

It can be seen from above that special inspections (including non-destructive testing) is carried out either to investigate a concern or perceived problem, or as part of condition monitoring programme where it is the most appropriate method for the routine inspection of a particular asset or part of the asset.

D3 Railtrack

D3.1 Introduction

Railtrack owns a wide range of structures, These consist of around 40,000 bridges and viaducts, around 700 tunnels, as well as embankments, culverts and supports for fixed equipment. Many of these are over 100 years old and all require proper management to continue functioning properly.

As each of the 40,000 bridge structures receives a six-yearly detailed examination, components of the structure are given a condition rating. From these an overall condition score is derived, based on the relative importance of each component. The condition is used to assist in the prioritisation of work, and provide a basis for the regulatory performance measure. In addition the system will demonstrate the change in condition of the bridge stock with time.

Persons who have met the requirements of Railtrack's standard of competence for the examination of structures carry out inspections according to Railtrack's technical specifications. These specifications include the frequency of inspection, pre-inspection activities, actual inspection process, inspection recommendations and reporting.

D3.2 Inspection

The objective of the inspection is to provide a quantitative condition mark for each asset that undergoes a detailed examination. The structure is marked on a scale of 0 to 100, where a mark of 100 indicates a bridge in perfect condition.

Having identified the minor elements of the bridge, the defects are identified and the visual condition assessment carried out, based on a prepared severity and extent rating tables, developed for each type of material (Ref. 11). An extensive photographic database is given in the guidelines with examples provided to illustrate defect types and extents in order to assist the Inspector in his assessment.

In addition to visual inspection, other testing techniques including non-destructive testing are routinely carried out where a risk assessment of the structural element has identified the need for them, or where such need arises out of a routine inspection recommendation.

APPENDIX E

EXAMPLES OF DAMAGE – SYMPTOMS CATALOGUE

APPENDIX E – EXAMPLE OF DAMAGE - SYMPTOMS CATALOGUE

Concrete Structures	Drying shrinkage	Plastic shrinkage	Settlement Shrinkage	Corrosion of reinforcement	Freeze-thaw action	Freezing of fresh concrete	Alkali aggregate reaction	Chemical dissolution Sulfate attack	Sulfate attack	Acid attach	Salt attack	Temperature gradients	Temperature gradients in curling	Cavitation	Running water/particles	Overloading/Underdimensioning	Faulty Concreting
Spalling, peeling, delaminations	●			●	●		●				●	●					
Spalling along reinforcement bars				●													
Cracks along reinforcement bars		●	●	●													
Diagonal fissures/cracks	●												●			●	
Random cracks/fissures	●	●			●	●						●	●			●	
Transversal cracks/fissures													●			●	
Dark, humid fissures	●						●	●									
Pattern cracking, checking	●	●			●		●		●	●	●	●	●				
Fissures with efflorescence				●			●	●									
Exudation							●										
Salt-calcareous efflorescence								●									
Rusty efflorescence				●													
Crumbling disintegration					●	●	●		●	●	●	●					
Accumulation of coarse aggregates																	●
Deflections/deformations							●									●	●
Crushing																●	
Surface erosion/pitting					●									●			
Leakage	●		●									●	●				●

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Earth Embankment	Internal Erosion				External Erosion				Quality of Materials and Construction						
	Low filer quality	Arching effects	Separation during construction	Foundation seepage	Wave action	Wave overtopping	Erosion due to ice action	Precipitation/flood	Low quality of materials	Limited compaction effort	Single graded materials	High rate of construction	Frost heave	Topography of the site	Steep slopes of dam
Damage/symptom															
A. Abnormal leakage															
Leakage with suspended material	●	●	●	●											
Leakage, no suspended material			●	●					●		●				
Soaked areas				●											
B. Abnormal deformations/settlements:															
Large deformations								●	●	●					
Uneven deformations										●	●	●	●		
Differential settlements														●	
Sinkholes	●		●	●	●									●	
Bulging of slope							●								
Transversal cracks														●	
Longitudinal cracks									●	●					
C. External erosion															
Damage on rip-rap					●		●						●		
Damage – top or downstream slope						●		●					●		
Damage upstream foundation					●										
Damage downstream foundation				●				●							
Floods, overtopping								●							

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