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Review of NDT methods in the assessment of concrete and masonry structures

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Abstract

This paper reviews the state of non-destructive testing (NDT) methods as applied to the civil engineering industry in the Millennium Year, 2000. The basic principles of NDT methods are described with particular reference to the five major factors that influence the success of a survey: depth of penetration, vertical and lateral resolution, contrast in physical properties, signal to noise ratio and existing information about the structure. The main NDT methods used in engineering investigations are discussed and illustrated with brief case histories from the literature. The integration of NDT surveys into the investigation of structures is described. The underlying reasons why NDT methods are perceived as 'not working' by the structural engineer are identified as: a lack of understanding of variability of both the construction materials used and NDT methods themselves. © 2001 Published by Elsevier Science Ltd.

Keywords: NDT; Concrete; Masonry; Radar; Sonics; Conductivity; Bridges; Buildings

1. Introduction

Non-destructive testing (NDT) methods clearly have a role in the evaluation and testing of civil engineering structures but all too often they are used to provide discrete information on specific problems rather than as an integral part of the overall survey programme. So, in this paper the fundamental principles of NDT methods are considered in some detail with a view to establishing a definitive role for them in the structural evaluation programme. Part of this role must be the setting of agreed standards and guidelines both for the execution of each surveying method in the field and the interpretation of the physical data obtained as an integral part of the investigation programme. The involvement of the NDT specialist as an essential part of the investigation team is long overdue on the majority of major civil engineering projects worldwide.

Many of the methods that are widely used in the NDT of civil engineering structures and materials are also commonly used in the engineering geophysical industry, particularly in the site investigation process for civil engineering construction projects. While scientists and engineers in the NDT area are not geophysicists in the classical sense of the word, nevertheless their activities in the NDT of structures are controlled by the same physical parameters that control the effective use of geophysical methods in the geological environment. For example, ground penetrating radar (GPR) is applied most effectively to the testing of both masonry arch bridges and concrete bridges, but in the NDT industry the method is more commonly referred to as the impulse radar method. It is, therefore, considered that the term 'geophysicist' can be applied to scientists and engineers working in the NDT industry. There is a wide range of NDT methods, which are used in the civil engineering industry, and examples of these techniques appropriate to bridges are summarised in Table 1 [1].

The application of NDT techniques to the solution of civil engineering problems has sometimes been disappointing. This has arisen from either using a method which lacked the precision required in a particular structural investigation or by specifying a method that is inappropriate to the problem under consideration. In some cases, these problems could have been avoided by taking expert advice before initiating the survey. It is also emphasised that in other cases, the physical condition of the structure was far more complex than anticipated at the planning stage of the NDT survey and hence interpretation of the data did not yield the information expected by the engineer.

It is often advisable to undertake a feasibility study on the structure to assess the suitability of the proposed NDT techniques for the investigation of the structural problem. Such a procedure might be referred to as a "desk study" [2].

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Table 1
NDT tests for bridges

Inspection method	Parameter measured	Advantage	Disadvantage	Cost
Visual	Surface condition	Quick; modest skills required	Superficial	Low
Proof load test	Load carrying capacity	Definitive	Very slow and possibly dangerous	Very high
Coring	Specific internal dimensions	Definitive dimensions	Measurement only at test point; scars the bridge	Moderately high
Vibration testing	Mode shapes and/or signature	Gives some indirect measure of current condition	Difficult to quantify data; heavily damped masonry bridges give yield little response	High
Impact testing	Mode shapes and/or signature	Gives some indirect measure of current condition	Difficult to quantify data; heavily damped masonry bridges give yield little response	Moderate
Ultrasonic NDT	Wave velocities through structure	Relatively quick	Only works on individual masonry blocks due to signal attenuation; no information on major elements	Moderate
Sonics	Wave velocity; tomographic cross-sections	Moderately slow; gives useful information on major elements	Requires skill to interpret data	Moderately high
Conductivity	Relative conductivity	Quick; gives relative conductivities over a large area to a maximum depth of 1.5 m	Limited depth penetration of 1.5 m; complements radar	Low
Radar	Electromagnetic wave velocity	Quick; can give good penetration; can give good image of internal structure	Poor penetration through clay infill and salt contaminated fill; requires skill to understand data	Moderately high

However, the key issue is to undertake a systematic and holistic investigation — an example for a bridge is given below:

Phase 1: visual inspection.

Phase 2: analysis of load carrying capacity.

Phase 3: review need for further investigation — if none, then revert to routine visual inspection schedule. If further investigation required, then proceed to Phase 4.

Phase 4: "desk study" — before undertaking any more detailed field study, research needs to be undertaken of the origins of the bridge, who designed and built it and the possible style of construction such as soil backfill or cellular construction. See Ref. [3] for further data on historical records of bridges.

Phase 5: cost effectively choose the most suitable strategy for further investigation — see Table 1. An NDT method may be chosen for one of two reasons: (a) when a direct physical measurement strategy was inadequate or too expensive; and (b) when there is a need to extend a limited physical investigation.

Phase 6: implement the investigation technique.

In this paper the major NDT methods used within the civil engineering industry are summarised together with their advantages and limitations. Other less well-known methods are also discussed with the objective of familiarising the reader with the complete range of methods, which might be suggested for the solution of a specific problem. It is essential to distinguish between methods that are considered to be state of the practice and those that are under development and are described as state of the art. The latter methods are likely to be specific to one organisation where the original research and development was carried out and should be used with caution until sufficient experience of their application in the civil engineering industry has been achieved.

2. Basic principles of non-destructive testing methods

There are many NDT techniques, each based on different theoretical principles, and producing as a result different sets of information regarding the physical properties of the structure. These properties, such as compressional and shear wave velocities, electrical resistivity and so on, have to be interpreted in terms of the fabric of the structure and its engineering properties. Inevitably, this interpretation involves some degree of assumption about the structure, and the use of calibration measurements is an essential feature of most non-destructive surveys. Furthermore, many structural problems will be best studied by a particular NDT method, depending upon which physical properties of the construction materials offer the best chance of being reliably determined.

There are five major factors, which need to be considered

Table 2
GPR Propagation through concrete and masonry where ϵ_r = dielectric constant (real)

Material	ϵ_r	Frequency (MHz)	Velocity (cm/ns)	Wavelength (cm)	Resolution (cm)	Z_{min} (cm)	Penetration (cm)
Stone parapet	5.69	900	12.55	13.9	7	4.6	Low
Concrete	9	900	10	11.1	5.6	3.7	Low
Stone parapet	5.69	500	12.55	25.1	12.6	8.4	Medium
Concrete	9	500	10	20	10	6.7	Medium
Stone parapet	5.69	100	12.55	125.5	62.8	41.8	High
Concrete	9	100	10	100	50	33.3	High

in the design of a NDT survey, as follows:

1. the required depth of penetration into the structure;
2. the vertical and lateral resolution required for the anticipated targets;
3. the contrast in physical properties between the target and its surroundings;
4. signal to noise ratio for the physical property measured at the structure under investigation;
5. historical information concerning the methods used in the construction of the structure.

Careful application of all the above factors to the design of a NDT survey should result in a specification which either achieves the desired objectives or, more importantly, recommends an alternative approach if no NDT surveying method is deemed appropriate to the solution of the problem specified. Some examples of the importance of these factors are presented below; the principles of the different methods that can be used are described later in the text.

The most common problem that an NDT specialist faces in dealing with the client during the investigation of a structure is the integration of the fundamental information derived from the construction records with the results from the NDT survey. The construction record plus any additional engineering assessment represents the most accurate information that can be obtained on the structure in the area of the investigation. The actual resolution that can be achieved with all NDT methods will be inferior to the precise measurements obtained from the original plans of the structure. For example, vertical resolution is defined as the smallest vertical dimension Z_{min} that can be detected, and this is normally expressed as:

$$Z_{min} = \lambda/4$$

where λ is the dominant wavelength of the NDT data being analysed.

In the case of an impulse radar survey, the resolution achieved is a function of the frequency of the incident electromagnetic energy and its velocity of propagation. Practical use of impulse radar indicates that the shallowest target that can identified below the surface of a structure is $\lambda/3$ [4] and within a structure the minimum size of target is a value of $\lambda/2$ [5]. The differences that the NDT interpreter is faced with can be illustrated by the following calculations incorporated into Table 2.

Clearly from the calculations it is important to select the optimum frequency to achieve the maximum penetration into a structure coupled with the required resolution of the likely targets.

It is also essential that there is a contrast in the physical properties of the materials within the structure — since there will be no resolution of any significant changes in the engineering properties unless these give rise to contrasts in physical properties, such as sonic velocity, dielectric properties and so on. Different physical properties can also be a problem; for instance, there is very little difference in sonic velocity between a material saturated with fresh water and one saturated with a saline solution. The same materials would be significantly different as far as electromagnetic properties are concerned since the material saturated with a saline solution will have a much higher attenuation coefficient than the one saturated with freshwater.

3. Non-destructive methods and their application

3.1. Sonic/ultrasonic methods

Non-destructive sonic and ultrasonic testing methods are non-invasive and have been used for the past thirty years in the assessment of civil engineering structures and materials. The sonic method refers to the transmission and reflection of mechanical stress waves through a medium at sonic and ultrasonic frequencies.

The five most commonly used sonic methods are:

- Sonic transmission method.
- Sonic/seismic tomography.
- Sonic/seismic reflection method.
- Ultrasonic reflection method.
- Sonic resonance method.

3.1.1. Sonic transmission method

Direct transmission involves the passing of a compressional wave at frequencies between 500 Hz and 10 kHz through the thickness of the wall (or the structure) under investigation. Transmission of the wave is initiated on one side of the structure by the impact of the force hammer,

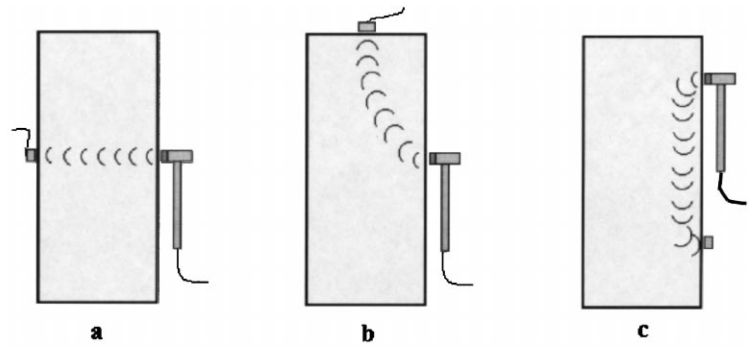

Fig. 1. Transmission modes for sonic wave tests: (a) direct; (b) semidirect; (c) indirect.

and reception on the opposite side is performed by an accelerometer positioned directly opposite the force hammer (Fig. 1a). The resulting wave velocity is an average of the local velocity along the path and it is not possible to establish the position and the extent of any possible inhomogeneity. The velocity magnitudes may be plotted in a contour map format, with grid points as X and Y co-ordinates and the pulse velocity as the Z co-ordinate. This format allows a simple evaluation of the relative condition of the masonry or concrete walls of the structure or an evaluation of the internal fabric of a structure, such as a masonry arch bridge.

Fig. 1b and c illustrate indirect transmission modes — used mainly for tomographic surveys.

It has generally been recognised that the direct transmission arrangement is a simple technique to apply in the NDT of structures since it provides a defined path length through the structure. Furthermore, since the arrival time of the first wave is of primary concern, no attempt to distinguish complex wave frequencies and reflections is required for the analysis. This method has been successfully used to evaluate material uniformity, detect the presence of voids, estimate the depth of surface crack, and calculate an average compressive strength for the structure or the material. The detection of flaws is possible due to the fact that sonic waves cannot transmit across an air gap, which could be due to a crack, void or delamination at the interface between brick or stone and mortar. A propagating wave must find a path around the void, resulting in attenuation and an increase in the transit time of the signal.

3.1.2. Sonic/seismic tomography

Sonic tomography represents an improvement in the sonic transmission test method because tests are performed not only in the direct mode but also along paths which are not perpendicular to the wall surfaces. The wall of the structure or the masonry section is thus crossed by a dense net of raypaths, each of which relates to a specific travel time between the sonic source and receiver through the structure. These values of travel time can be used to compute a three-dimensional reconstruction of the velocity distribution across the structure or selected cross-section so that local variations in velocity can be identified and correlated with zones of weakness or flaws in the internal fabric of the structure. An example of such a set-up on a 100 + year old twin arch stone masonry bridge is shown in Fig. 2 [3].

It is usual to assume a linear structural response in the application of the tomographic method. This is because the response is measured with transducers which are normally

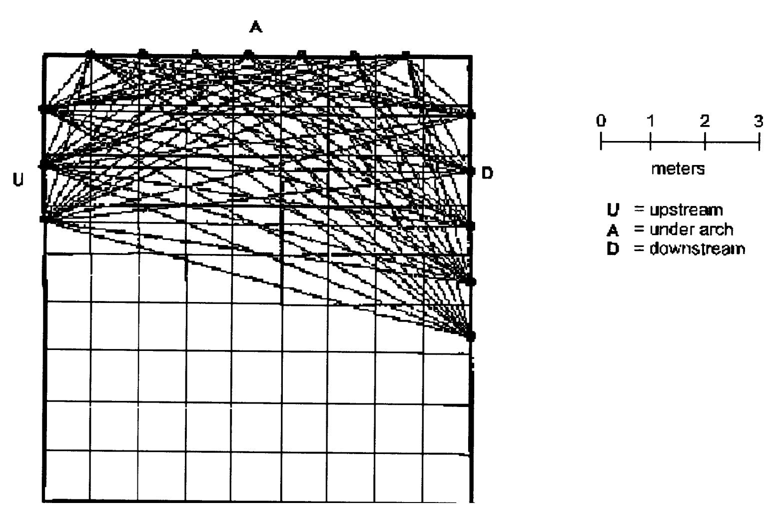

Fig. 2. Middleton bridge (2 m level): initial assumed density of sonic ray paths.

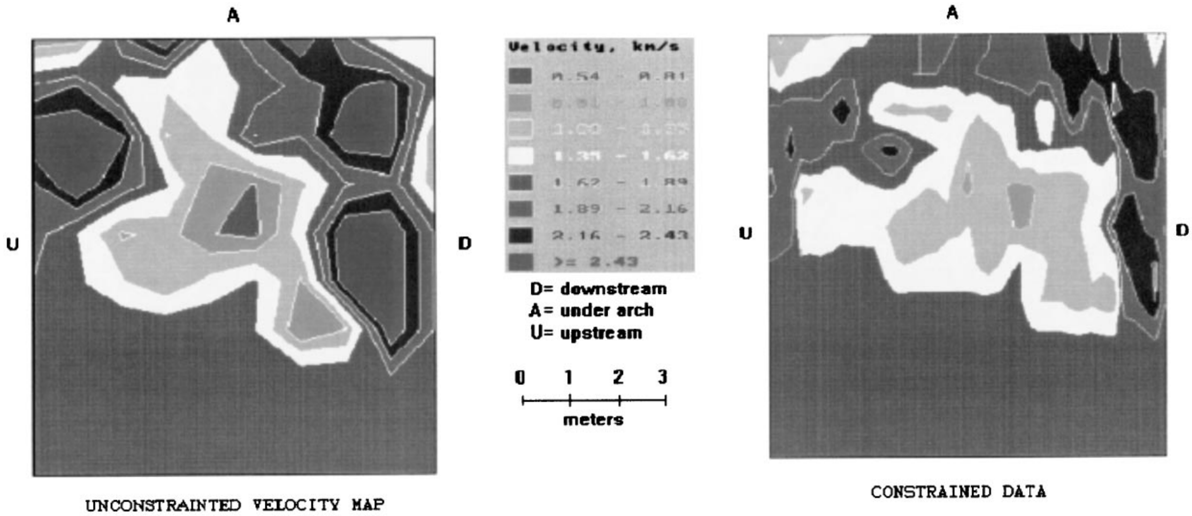

Fig. 3. (a) Sonic unconstrained data. (b) Sonic constrained data.

mounted well away from the location of the impact where non-linear behaviour may arise. Any variation from the expected travel time is therefore attributed to in-homogeneity in the structure or damage occurred. In order to obtain good statistical accuracy it is necessary to maximise the amount of experimental data included in any calculation used by ensuring that all areas of the proposed tomographic section have adequate raypath coverage. A number of inversion algorithms are available commercially for tomographic reconstruction.

Data acquired usually exhibits a good deal of velocity scatter, resulting from variations in the strength and nature of the hammer hit generating the input signal, the interpretation of acquired waveforms by the operator and coupling of the receiving transducer to the masonry or concrete surface. Data scatter has the effect of increasing the residual of tomographic velocity reconstruction and may lead to identification of false anomalies. The accuracy of the velocity reconstruction can be improved by a better understanding of the input signals, by a carefully planned choice of position and number of the reading stations and by simple data smoothing prior to analysis.

An example of a sonic tomographic interpretation of a masonry twin arch bridge abutment is given in Fig. 3 (a) and (b). The unconstrained velocity map refers to the situation when no knowledge exists about the structure. A constrained map is when some knowledge of the structure is entered into the analysis model.

3.1.3. Sonic/seismic reflection method

In the sonic reflection method both the initiation and reception of the sonic wave are performed on the same face of the masonry as in the case of indirect transmission, but the stress wave recorded is the direct stress wave reflected from any internal flaw or the rear face of the structure investigated. The value of velocity calculated from the rear wall or face of a structure is a measure of the local velocities along the path.

The problems that reflection methods may be used for in the investigation of retaining walls/wing walls/spandrel walls are:

- Internal dimensions and shape.
- Type and properties of fill.
- Voiding within the fill material.
- Cracks and voids within the internal fabric of the structure.

Seismic waves, which are also generated by an impact source, are commonly referred to in NDT applications and propagate at frequencies in the range from 100 Hz to 1 kHz. However, the terms sonic and seismic are often interchanged in practice, since both refer to the propagation of compressional waves in a medium. Seismic reflection techniques may be employed from the road surface, arch barrel or spandrel walls of a masonry arch bridge, the front of a retaining wall, or a harbour dock wall. However, it is not a method currently recommended since the resolution achievable with the low frequency energy is poor and it is often difficult to distinguish reflections from surface waves and refracted arrivals.

3.1.4. The impact–echo system

The most recent development of sonic/ultrasonic methods is known as the impact–echo test method, which was originally developed to measure concrete thickness and integrity from one surface. The method is performed on a point-by-point basis by using a small instrumented impulse hammer to hit the surface of a structure at a given location and recording the reflected energy with an accelerometer mounted adjacent to the impact location (Fig. 4). Since reflected signals are more easily identified in the frequency domain, the received

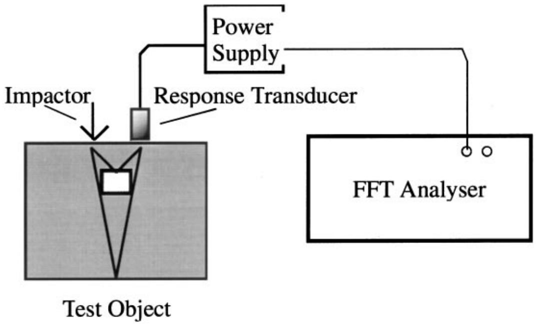

Fig. 4. Set-up for impact–echo test.

energy recorded in the time domain is passed to a signal analyser for frequency domain analysis — using a fourier transform algorithm such as fast Fourier transform (FFT). A transfer or frequency response function (FRF) is then calculated for the impulse hammer/accelerometer system and reflections or echoes of the compressional wave energy are indicated by pronounced resonant frequency peaks in the transfer function or frequency spectrum record (Fig. 5). These peaks correspond to the thickness or flaw depth resonant frequencies and knowing the compressional wave velocity in concrete or any other construction material the depth to the corresponding flaw can be calculated. The depth of the reflector will correspond to the slab or wall thickness if the concrete used in construction is sound. The original concept of FRF testing of civil engineering structures dates back to the testing of concrete piles [6], whilst the modern adaptation was undertaken at NIST (National Institute for Standards and Technology, USA) and Cornell University [7–9].

Impact–echo testing of bridges has largely been focused upon identifying voids in ducts in post-tensioned concrete bridges. Finite element (FE) analyses of a laboratory experiment at the University of Edinburgh showed that defects can be identified provided a sufficiently high frequency is used: $>\lambda/2$ with respect to the defect [5].

In practice it is often not that straightforward. Results from a laboratory scale investigation at the University of Edinburgh, indicated that the experimental results were not as unambiguous as the FE work. This ambiguity is due to a number of potential reasons:

- Three-dimensional dispersion of the impact–echo wave through the concrete due to the presence of aggregate and other in-homogeneities.
- Possible reduction in frequency of the impact–echo signal due to crumbling of the concrete surface resulting in longer contact time and thus lower frequency [10].
- Possible lack of sensitivity of the ultrasonic transducer.

3.1.5. Ultrasonic reflection method

Ultrasonic waves, which are generated by a piezoelectric transducer at frequencies above 20 kHz propagate with a wavelength around 50–100 mm in masonry. This form of testing is used successfully at ultrasonic frequencies for the detection of flaws in metal castings and is the first non-destructive technique that was developed for the testing of concrete. However, it is much less practical in concrete and masonry, which have much higher attenuation characteristics and hence lower frequency signals are required to obtain a reasonable penetration. In addition, the numerous material boundaries in these materials result in scattering of both incident and reflected waves. Despite this fact, it has been successfully used for identifying and locating specific flaws in concrete and is also applicable to the investigation of small defects within masonry walls.

However, at present the method is not commonly used for these purposes due to a number of technical difficulties. In the case of ultrasonic signals the main factors to overcome are the need for good coupling of the transducer to the surface, which is often rough, and the scattering of the wave due to material heterogeneity. The need for effective coupling requires the use of a coupling agent, such as grease or petroleum jelly, to temporarily adhere the transmitter and receiver to the surface. This makes the process of moving the points of measurement quite slow and it is often difficult to achieve adequate coupling on some uneven surfaces. Scattering of the signal limits the propagation through the material and also leads to a complicated series of return signals. This makes it difficult to identify defects amongst the noise. In addition, surface waves, which travel more

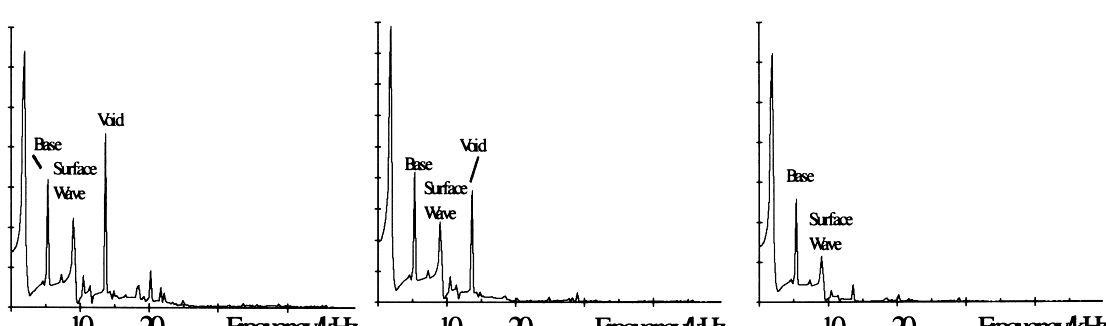

Fig. 5. Frequency spectrum obtained after impact with hammer on test wall.

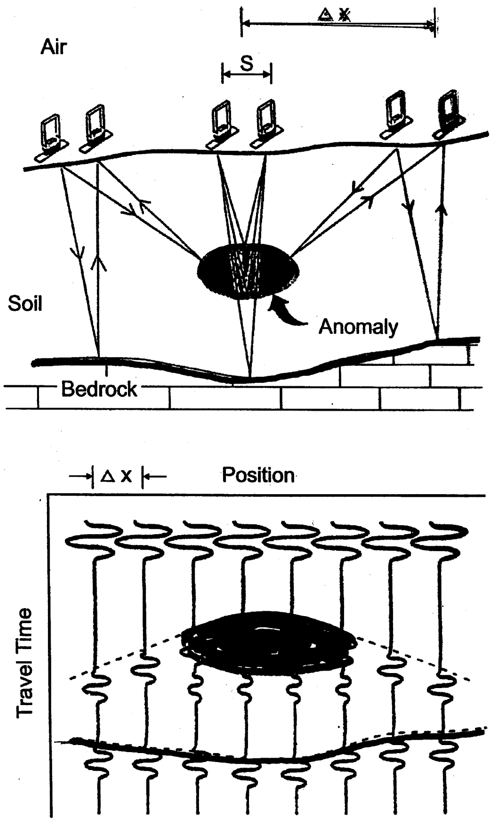

Fig. 6. Basic principle of radar testing (after Annan [28]).

Fig. 7. The Bell Tower at Cremona, Italy.

slowly than the compression waves, may arrive at the receiver within the same time interval and confuse interpretation. Further developments of the ultrasonic technique, for example improvements in signal generation, detection and data processing are underway and may lead to a practical tool if the problems mentioned above are overcome.

3.1.6. Sonic resonance method or "coin tap" test

A simple variation of the impulse echo method described above has been carried out for many years in the UK to detect defects or cavities behind the linings of tunnels or areas of rendered wall where the rendering has separated from the brick or stonework. In this case the wall or lining is tapped with a lightweight hammer and the ringing or echo associated with a hidden cavity or defect produces a significant change in frequency as the impulse hammer is operated in the defective area. The method is rapid to use since the human ear is extremely sensitive to the change in the resonant frequency. An instrumented version of this test was developed and used successfully on a bridge in Scotland [11] to identify debonding of metal plates glued to the underside of a concrete deck.

3.2. Electromagnetic methods

3.2.1. Impulse radar

Impulse radar uses the same instrumentation as that described above for ground penetrating radar but usually deploys higher frequency antenna above 1 GHz to obtain the resolution required over the shorter distances involved in the testing of a structure [12,13]. In some instances, such as the evaluation of the internal structure of a masonry arch bridge or a harbour dock wall, greater penetration of the electromagnetic energy will be required and lower frequency antenna in the range 100–500 MHz will be used. The range of possible uses for the impulse radar method in the NDT of civil engineering structures is so wide that it is likely that the method will undergo significant development in this area over the next few years. For example, the UK Highways Agency has commissioned a study of the use of radar in the evaluation of masonry arch and concrete bridges [14]. The basic principles of radar can be seen in Fig. 6.

A radar survey was undertaken on the historic masonry Bell Tower at Cremona, Italy — Fig. 7. Fig. 8 shows a freehand interpretation of a radar pulse through a double leaf-skin masonry wall with an air void between the leaves. It shows how a simple signal can be compounded with multiple reflections at the various air interfaces. This type of analysis can be critical in terms of assessing the stability of a heterogeneous structure such as a bell-tower [15].

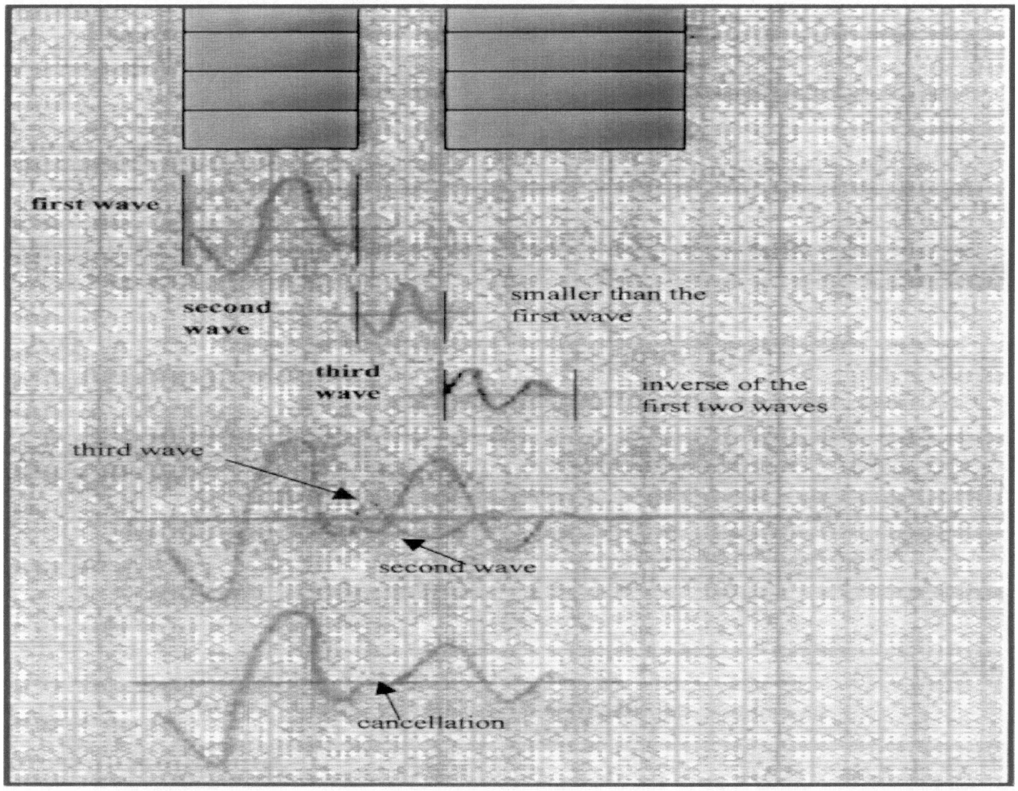

Fig. 8. Free-hand interpretation of GPR wave at the Bell Tower at Cremona, Italy.

3.2.2. Conductivity measurements

The electromagnetic conductivity of a concrete or masonry structure is a function of the degree of the water saturation of the materials within it and their electrical properties. Electromagnetic fields are propagated into the structure and variations are monitored and recorded. These provide geometrical and electrical information on the materials investigated and their degree of saturation. The simple equipment in current use is non-contacting, so that no surface mounted devices are required, and very rapid to deploy. Problems can arise when reinforcing rods are present within a concrete structure [16].

Water ingress and moisture movement into structures is important in terms of structural durability. For example, if the road surface of a brick masonry arch bridge permits water entry then the soil fill above the arch barrel may become saturated. This can result in degradation of the mortar between the bricks — giving rise to premature failure. Another example of water inclusion in masonry structures is due to moisture capillary rise from the building foundations. The architect or engineer may want to know what is the actual height of water rise in the inside of the wall — this height is generally greater than that observed on the external wall surface. This latter problem can also be addressed using GPR [17].

In the majority of the cases, salt content is associated with water content in the structure. This phenomenon can also cause great damage to the structure and rapid decay of the masonry wall, and it is therefore a cause of concern. Thus a non-invasive method of determining moisture movement behind or inside the masonry walls is of great engineering value.

Conductivity measurements can be used to assess:

- moisture content in the masonry;
- salt content in the masonry associated with moisture content;
- height of moisture capillary rise;
- thickness of the masonry wall;
- multi-wythe nature of the masonry wall;
- composite construction of the masonry structure;
- presence of voids or in-homogeneities in the wall;
- presence of metal reinforcements, pipes, drains etc. in the wall.

Fig. 9 shows the results from a conductivity survey on the wingwall of a 100-year old masonry arch bridge [18]. The pink shaded area represents an area of high conductivity — possibly due to ingress of de-icing salt and rainwater.

3.2.3. Covermeter

Electromagnetic methods are also commonly used to determine the location and thickness of concrete overlying the reinforcement rods embedded in the concrete. The instrument used commercially is known as the covermeter

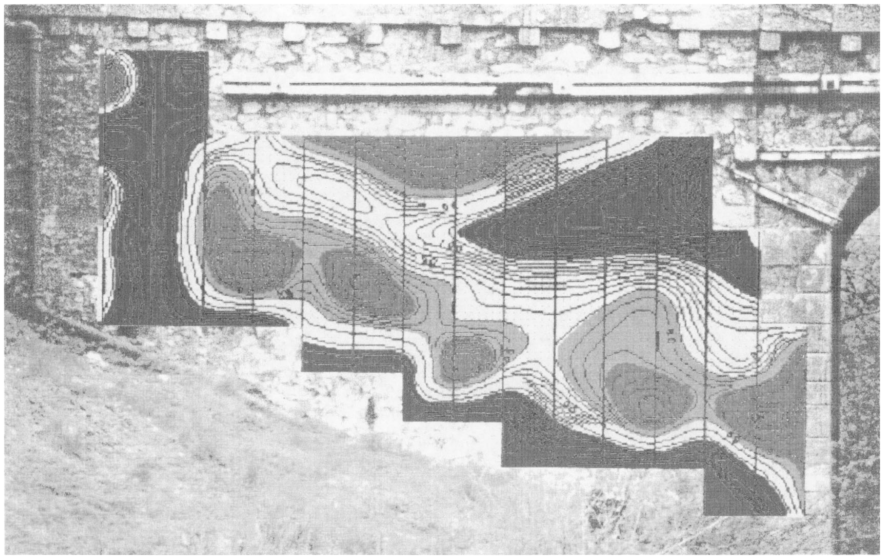

Fig. 9. Conductivity distribution on downstream side up to 1.5 m depth.

and is based on the principle that the presence of the steel rod within the concrete affects the field of an electromagnet.

The covermeter consists of two coils positioned on an iron-cored inductor. When an alternating current is passed through one of the cores a current is induced in the other, which is then amplified and measured. The influence of steel on the induced current has a non-linear relationship with the thickness of the concrete and is also influenced by the diameter of the rod. However, modern covermeters are designed and calibrated to accommodate these effects and with careful application excellent results can be achieved. It should be noted that if the concrete has been penetrated by saline water the increased electrical conductivity of the concrete above the reinforcing rods may affect the accuracy of the results measured on the covermeter. More recent and specialised applications involve the sizing of re-bars using covermeters [19].

3.3. Electrical methods

3.3.1. Resistivity measurements

A miniature version of the electrical resistivity method can be used to assess the likelihood of significant corrosion within a reinforced concrete structure [20]. The electrodes are deployed in a constant separation Wenner array and are used to map the variation of electrical resistivity over the surface of the structure or beam. These changes can be related to the ability of corrosion currents to flow through the concrete, which is a function of water/cement ratio, the moisture content and the salt content. The major problem associated with this method is that of achieving good electrical contact between the electrodes and the concrete structure and it is usually necessary to drill small holes to provide effective contact.

3.3.2. Half-cell potential measurement

The more popular method for assessing corrosion of the reinforcing rods is the half-cell potential system where the potential of the embedded steel reinforcement rod is measured relative to a reference half-cell placed on the concrete surface. Zones of varying degrees of corrosion risk can be identified by preparing potential contour maps on the concrete surface and these are particularly applicable for assessing maintenance and repair requirements. It is most valuable in the comparison of areas where corrosion has already been evaluated with those where the corrosion risk has yet to be established. Again contact is necessary with the steel reinforcing rod and a small hole has to be drilled through the concrete. Generalised corrosion risk is reflected by uniformly low potential measurements while localised corrosion is indicated by high potential gradients, which appear as ‘whirlpool’ effect. Interpretation and presentation of the data obtained is similar to techniques described above for geophysical methods and the data could, for instance, be displayed in a shaded relief format.

An example of a half-cell survey and the ensuing results are given in Fig. 10 [21].

3.4. Infra-red thermography

Infra-red thermography is a process in which heat at any temperature can be converted into a thermal image using specialised scanning cameras. It has been observed that buildings or structures with defects such as debonding render and mosaic or delaminating concrete emit differing amounts of infra-red radiation. If a concrete surface with an even colour and texture is viewed with an infra-red camera it will appear quite uniform when the concrete is free of defects. However, if there are any cracks or delaminations

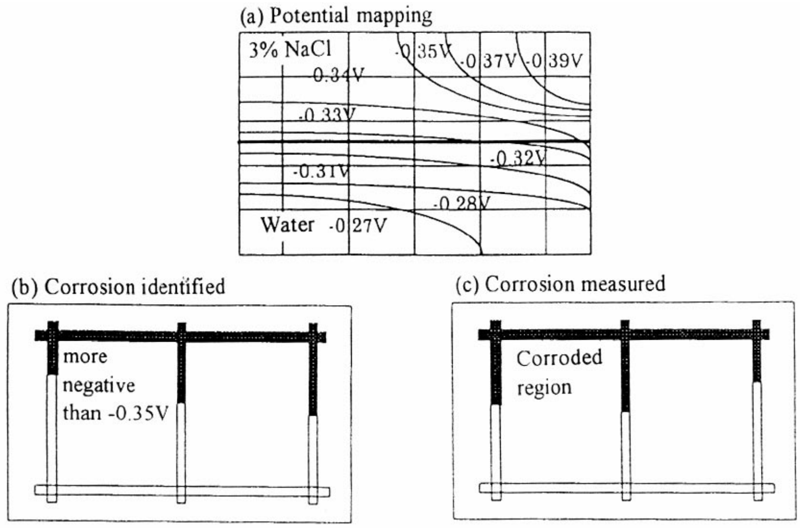

Fig. 10. (a) Potential mapping at the bottom surface of the RC slab at 250 h elapsed in the electrolyte test. (b) Identified corrosive region of rebars by the simplified BEM analysis based on the ASTM criterion. (c) A result of visual inspection of rebars [20].

within the concrete the surface will heat up faster under solar irradiation in these areas and hot spots will be observed in the thermal record. These areas can then be examined more closely and marked on the structure for identification and future investigation. This method has proved to be most effective as a reconnaissance tool for the rapid assessment of large buildings particularly high rise apartment blocks [22] — Figs. 11 and 12.

3.5. Radiography

Very short wavelength electromagnetic radiation, namely X-rays, gamma-rays or neutron rays, will penetrate through solid media but will be partially absorbed by the medium. The amount of absorption, which will occur is dependent upon the density and thickness of the material which the radiation is passing through, and also the characteristics of the radiation. The radiation which passes through the material can be detected and recorded on either film or sensitised paper, viewed on a fluorescent screen, such as a television screen, or detected and monitored by electronic sensing equipment.

Radiography is capable of detecting any feature in a component or structure provided that there are sufficient differences in thickness or density within the test piece. Large differences are more readily detected than small differences. The main types of defect, which can be distinguished, are porosity and other voids and inclusions where the density of the inclusion differs from that of the basic material. Generally speaking, the best results would be obtained when the defect is an appreciable thickness in a

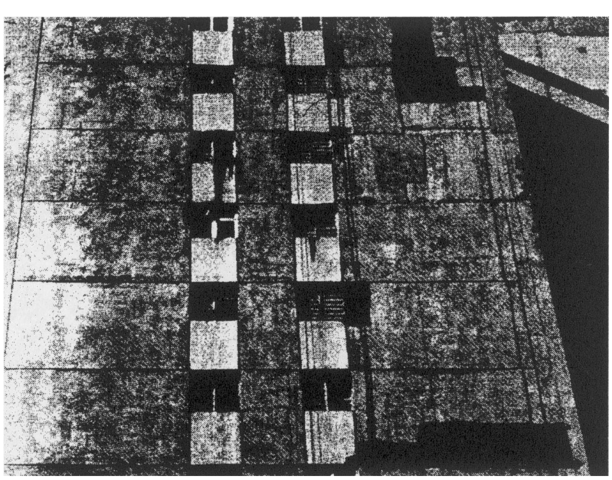

Fig. 11. Wall of a rendered building in Hong Kong that is seriously debonded. It is being repaired on the right of the photograph, but left was not noted as being in need of repair. The thermogram (Fig. 12) shows the extent of debonding [21].

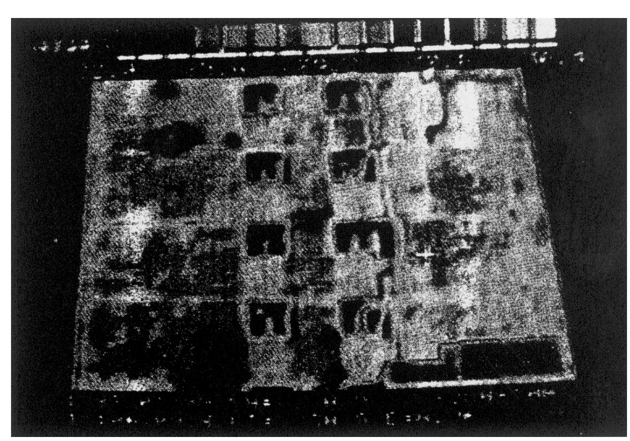

Fig. 12. Computer enhanced thermogram. Wall of a rendered building that is seriously debonded. This can be seen from the dark areas on the left of the thermogram. The area (bottom right) is a recently completed repair [21].

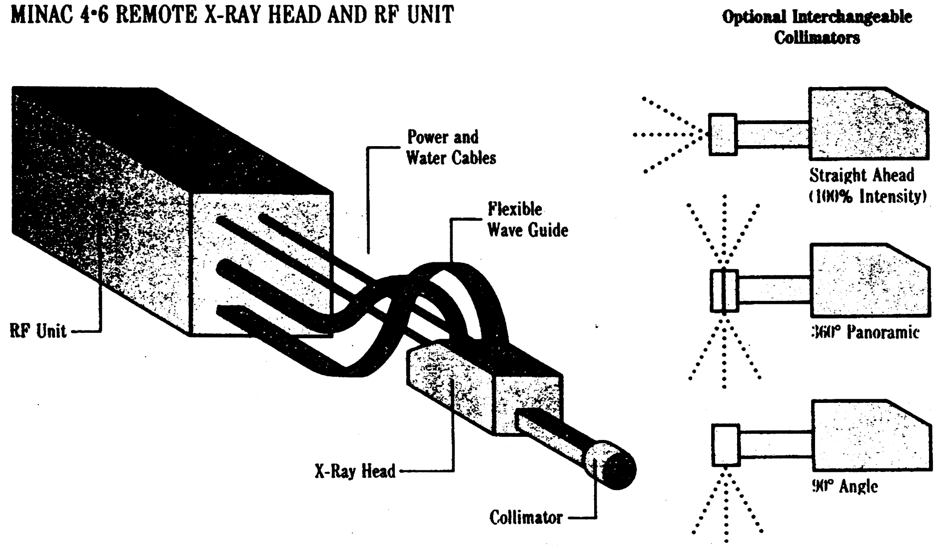

Fig. 13. Standard MINAC assemblies [23].

direction parallel to the radiation beam. Plain defects such as cracks are not always detectable and the ability to locate a crack will depend upon its orientation to the beam. The sensitivity possible in radiography depends on many factors but generally if a feature causes a change in absorption of 2% or more compared to the surrounding material, then it will be detectable.

Radiographic techniques are frequently used for the checking of welds and castings and in many instances radiography is specified for the inspection of components as discussed above [23].

3.5.1. X-ray systems

X-rays require an instrumentation system employing an electrically powered linear accelerator to generate X-rays. As will be appreciated from the medical use of X-rays, significant precautions need to be taken with regard to the use of personnel in the vicinity of an X-ray. Thus when having an X-ray undertaken upon a patient one has to wear a lead protective apron. These precautions are for low powered X-rays which are adequate for checking fractures or bone structure shapes such as the spine and only low doses of radiation are necessary. However, in electrically "lossy" materials such as concrete much higher doses of X-ray are required to be effective and thus safety becomes a paramount issue. Higher dosages of X-ray can be used where the component can be put into a sealed container as occurs when one is X-raying baggage at an airport, but when working on a construction site this is a totally different application. A specialist and potentially cost effective application of radiography includes checking for voiding in post-tensioned bridge structures. The instrumentation system used in this instance is the French "Scorpion System" but the very high dosage of X-rays means that an exclusion zone up to a 1000 m may need to be cleared of human beings and cattle. However, the plus side is that the Scorpion system with high powered X-ray gives an instant view of the inside of a post-tensioned bridge duct on a television monitor which is then video recorded for future analysis. An example of a portable system is the MINAC assembly from the Schonberg Research Corporation [24] — see Fig. 13.

3.5.2. Gamma-ray systems

Gamma-rays involve a nuclear source and require the nuclear probe to be brought into contact or into a hole drilled in the structure. This technique is less potentially dangerous than X-rays provided that the nuclear source is carefully controlled. However, the gamma-ray procedure emits far less power than the X-ray system, the images tend to be weaker and require longer "stacking" time. Thus a survey which might take 30 min using a high powered X-ray, would take several hours using a gamma-ray procedure.

In terms of safety, if something goes wrong then the X-ray can be switched off as it is an electrically generated system. However, the gamma-ray system cannot be switched off as it is a nuclear source. Additionally, the gamma-ray source cannot be carried in a conventional motorcar without special facilities of a lined and protected box and various warning signs on the vehicle. Additionally the vehicle cannot be randomly parked at, for example, service stations on motorways and so on. Special licences have to be obtained for the carriage and use of gamma-ray sources. There are also limitations upon the health of workers exposed to gamma-rays and people who are particularly vulnerable either with health problems or pregnancy.

3.5.3. Neutron radiography

Neutron radiography is an established non-destructive testing technique for identifying internal details, materials and assembly. A neutron flux, which passes through an object, is differentially attenuated by the various materials present. This differential can be recorded on film as the flux emanates from the specimen, revealing details of the composition of the object. This is similar in many respects to X-ray radiography, in which X-rays constitute the radiation flux. Neutron radiography has recently been used to study internal cracking patterns in concrete by causing the cracks to absorb a contrast agent which readily attenuates neutrons [25–27].

The principles of the technique and the procedural details of performing neutron radiography on concrete specimens are discussed in detail in Refs. [25,27].

A study on neutron radiography of concrete in comparison to X-ray radiography was undertaken by Hover and Najjar [28]. Basically they compared neutron radiography techniques with a more conventional X-ray radiography [29]. They investigated a 4 mm thick disc cut from a 100 mm diameter concrete cylinder. A conventional photograph of this thick disc of concrete is shown in [29; Fig. 3a] neutron radiograph of this same specimen is shown in [29; Fig. 4] in which multiple cracks appear as white line-like images surrounded by dark images of both mortar and aggregate. These cracks have been impregnated with a neutron attenuating contrast agent prior to exposure to a neutron flux. The radiograph shows cracks, which are not visible under microscopic examination of the specimen at $40\times$ magnification. (Also shown on the radiograph are white circular spots, which indicate primarily the location of air voids. Porous aggregate if present may also appear as white spots.)

The neutron technique has been compared with the more conventional X-ray radiography — the neutron radiograph shows more cracking than the X-ray radiograph.

From the above it can be seen that neutron radiography does have a place in laboratory testing but cannot be used on large scale structures such as bridges very easily.

One has to consider that perhaps emerging technologies are more appropriate for NDT of concrete than some of these more dangerous techniques. For example radar techniques which are still at a development stage can be more effective for investigating moisture in concrete, voiding in concrete and positions of re-bars. However, it must be understood that radar cannot penetrate metals.

4. Discussion

Geotechnical and civil engineers are accustomed to referring to British Standards Institution and National Measurement Accreditation Service (NAMAS) standard testing procedures when requesting material testing and site investigations. These standard procedures assist them and the associated contractor in carrying out an investigation to a given set of instructions — it therefore appears to be reasonably straightforward for an engineer to specify, supervise or check the work carried out by the subcontractor.

However, engineers are surprised that when wishing to investigate structures using NDT methods they can find no appropriate British Standard, Code of Practice or NAMAS standard on which to base a tender specification and prepare a bill of quantities. The engineer can search in vain for a standard procedure for carrying out most NDT methods, the one exception being the recently published assessment of the use of impulse radar in the testing of concrete structures [30].

Frequently the question is raised as to why there are no clearly defined specifications or standards for the various NDT methods available for use in structure testing. It certainly is not for the want of trying by engineers and NDT specialists. There is a vast range of published case histories on the application of NDT methods in structural investigations in many civil engineering projects.

With all this information available it is difficult to understand why there is still the frequently expressed opinion of engineers that ‘NDT methods do not work’ and the complementary retort from the geophysicist that ‘all the engineer wants is the cheapest job’.

It would appear that the problem is a joint one:

1. Engineers have difficulty in understanding the variability both in the construction materials and geometry of the structure and what the NDT specialist can and cannot quantify.
2. NDT specialists have been slow to relate their measurements and interpretations to geotechnical and engineering parameters. NDT specialists, in general, have little or no training in civil engineering design and practice.

In summary, there are two independent groups of investigators with the same goal but with no agreed route to that goal. In a discussion on the application of geophysical methods to the site investigation process Annan [31] attempted to explain the difficulties: “Geophysics should be to the engineer what medical imaging is to the doctor. However, the geophysical problem is far more difficult than the medical problem. Normally the human parts are in the same locations.” The same comment is equally applicable to NDT of structures since in most cases there is very little positive information available on the internal composition of the structure under test.

It must be borne in mind when an NDT survey is being considered that there must be distinct differences in the physical properties of the subsurface target, and its surrounding material for the survey to provide the possibility of a success or as the engineer would say ‘make it work’. However, usually the detailed information required to specify an NDT survey is not available until after the survey has been completed and reported. So, how does the engineer proceed?

The engineer must become familiar with NDT methods since an NDT investigation is not a simple routine procedure but it is a piece of research in which experience and instrumentation are deployed to carry out an investigation. The message must surely be that if one is specifying or requesting a service one should be aware of the background to the techniques requested and their limitations.

The question of lowest contract price is a familiar discussion point and of concern to all, but it is a fact of life within and without the earth sciences profession that contract prices have decreased continually since the late 1980s. The NDT specialist will have to come to terms with the world of low and perhaps decreasing prices in the future and can only survive by being better trained, equipped and more efficient. Certainly the advent of NDT equipment incorporating computers and data loggers plus the savings in time and money of PC-based data display systems will assist.

While it is important to produce detailed NDT standards for structural investigations there appears to be ample technical literature either currently available or in the pipeline to ensure the availability of sufficient guides, guidelines and specifications for the correct specifcation of an NDT structural survey. What is missing at the moment is the close collaboration between the civil engineer and the NDT specialist that is essential for the successful outcome of the NDT survey at an economic cost.

5. The future

The future of NDT lies in the areas of:

- Better understanding of material properties.
- Better understanding of complex structures.
- Improved tomographic imaging.
- Forward modelling.
- A more realistic approach to the accuracy and achievable results from NDT.

Considerable progress has been made within the international community in order to identify the accuracy of various NDT techniques for the analysis of bridge reliability. However, the challenge from the professional community is to adopt these understandings when undertaking ultrasonic, impact–echo and radar surveys of structures. It is now clear that the null hypothesis approach using impact–echo testing that “if a defect is not seen then it does not exist” is too simplistic.

6. Conclusions

- A wide range of NDT techniques applied to bridges and buildings has been reviewed.
- Radar or GPR testing is a good investigative tool for both concrete and masonry buildings and bridges.
- GPR will not penetrate conductors such as metal or salt water.
- Radar will cross air voids — although the reflection signals can be very complex as seen from a delamination in a masonry wall.
- The shallowest detectable defect using radar is at a depth of $\lambda/3$.
- The best practical resolution of radar is $\lambda/2$.
- The null hypothesis approach using impact–echo testing that if a defect is not seen then it does not exist is too simplistic — thus impact–echo testing may be oversold.
- There is an urgent need to develop standards for NDT testing and interpretation in relation to structures.

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