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RILEM TC 127-MS: NON DESTRUCTIVE TESTS FOR MASONRY MATERIALS AND STRUCTURES

RILEM TECHNICAL COMMITTEES

Recommendations of RILEM TC 127-MS: Tests for masonry materials and structures

The texts presented hereunder are drafts for general consideration. Comments should be sent to the Chairlady:
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SUMMARY

There is considerable interest in the use of non-destructive (non-invasive) tests to investigate structures and determine the sub-surface arrangement of materials and their condition and whether any faults are present. This is particularly important for heritage masonry structures where large scale destructive tests, such as coring or dismantling would be unacceptable. These three test procedures are a first attempt by the late committee 127-MS to systematise such methodologies and to encapsulate a substantial body of experience gained to-date. The methodolgy will be developed further by committee MDT.

The tests are:

MS.D.3: Radar Investigation of Masonry

MS.D.4: Measurement of Local Dynamic Behaviour for Masonry

MS.D.8: Electrical Conductivity Investigation of Masonry

Category D: In-situ and non-destructive test proposed test method

MS.D.3: RADAR INVESTIGATION OF MASONRY

D.3. 1 CONTENTS

D.3.2 SCOPE

This recommendation specifies a method for radar investigation of masonry structures using impulse radar techniques. Details regarding the principles involved, the apparatus, the method of test, the method of calculation and the contents of the test report are provided. The impulse (shear) waves, of radio frequency may be introduced using antenna of varying centre frequency.

D.3.3 BACKGROUND

Historic structures such as cathedrals and masonry arch bridges rarely have accurate or perhaps any drawings of their construction. Considerable problems occur when it becomes necessary to assess the structural stability of a critical component of a complex structure. Examples include: bell towers of churches, the arch thickness and springer shape of both brick and stone masonry bridges, the shape of masonry gravity retaining walls. Within the European Community a special problem arises due to the increasing axle loads dictated by Community policies. One strategy currently adopted by bridge managers is to assess the load carrying capacity, if the bridge fails but looks OK – then the new strategy is "monitor". Thus non-invasive techniques such as radar have a growing role.

D.3.4 SITE APPLICATION OF THE TEST

Impulse radar testing of masonry structures can be used to identify:
– voids
– cracks of a planar nature
– wall thickness
– structural composition
– relative quality of the masonry
– capillary rise
– relative moisture content
– zones of salt content / contamination.

Some typical examples of such applications are described in [1, 2].

D.3.5 TEST LOCATIONS

Test locations are dictated by engineering objectives, however an attempt should be made to measure the variation in material quality or condition throughout the structure. Due to the rapid pulse repetition rate of radar (50 kHz) the structure can be tested rapidly. It is normal to test the structure in cross sections by scanning either longitudinally or vertically. Thus a series of traverses (horizontal of vertical) should be marked out for investigation - usually on a 1 metre or similar grid. Prior to this, a quick survey of material uniformity may indicate that certain areas are of greater interest than others. Generally, a significant length of traverse, at least 5 metres, will be required in order to obtain an adequate basis for comparison of the data.

D.3.6 PRINCIPLE OF TEST

The principle behind the test is one of applying an electromagnetic impulse to the structure. The electromagnetic impulse is emitted as a half sine wave via an antenna of a certain centre frequency. In between pulsing at 50 kHz the antenna switches to receiving mode. The data is stored in the time domain and may be displayed either on a computer screen or printed out on a chart recorder. The centre frequency should normally be in the range between 0.1 GHz and 1.5 GHz depending on the size and condition of the subject structure.

The wave may be travelling through a multi-layer system of brick, mortar, fixings and possibly a defective zone. The electromagnetic pulse will be partially transmitted and partially reflected at each boundary between materials, making up the masonry structure, which have differing dielectric properties. Significant cracks also behave as such boundaries because the wave has to pass from solid material to air and back to solid material when traversing the crack. Discreet zones of dampness or higher soluble salts content also act as boundaries because the higher electrical conductivity that results, alters the dielectric constant, but gradual or subtle variations in moisture or salts content are unlikely to be detectable.

D.3.7 CONDITIONS OF TESTING

Tests will be conducted under ambient conditions, however the work should not be carried out in heavy rain or other conditions as these will cause, severely erroneous results. Severe water ingression will significantly affect the results of a radar survey and saturated walls may cause such high attenuation that the returned signal is lost in the noise.

D.3.8 APPARATUS

The impulse radar system comprises a number of components:
– a radar pulse generator of varying pulse repetition rate;
– an appropriate centre frequency antenna;
– appropriate data recording system – either digital on tape or hard disk or analogue on paper.

D.3.9 PROCEDURE

The experimental procedure, will involve marking out the masonry in traverses either horizontally or vertically. The dimensions should be taken with considerable accuracy in order to enable subsequent mapping to be undertaken. A typical grid will be at 1m intervals.

The choice of antenna centre frequency depends upon the depth of penetration and the type of material to be tested and the test methodology – that is whether it is reflection mode or transmission mode:

Reflection mode:

– A 1 or 1.2 GHz antenna may be used for thin panel reinforced brick masonry particularly when attempting to identify reinforcing bars.

– For double skin masonry it may be necessary to use a higher power 900 MHz antenna.

– For the investigation of stone masonry it may be necessary to use lower frequency as low as 100 MHz in order to obtain credible data.

Depth to a target is calculated from d = (velocity x [time to reflection])/2 [units = metres] (but remember that in multilayer structures this calculation can get quite complex as the velocity is dependent on the dielectric constant).

Transmission mode:

– a 500 MHz antenna may be used for transmissions over short distances.

– a 100 MHz antenna is more appropriate for transmissions over longer distances.

The average velocity may be determined directly from the transmission tests where the antenna separation is known:

velocity = [distance travelled]/[time of flight] [units = cm/ns].

From the velocity, the average dielectric constant (e_r) of the material may be computed:

$$e_r = (c / v)^2$$

where, c = speed of light (a constant) and v = velocity (measured).

The problem with older lower quality masonry is that in electrical terms it is “lossy”. The many problems of antenna choice, together with solutions are discussed elsewhere [3, 4].

The specific settings for the radar system should be undertaken in accordance with the manufacturer’ s handbooks.

D.3.10 TEST RESULTS

The data may be expressed as the time to reflection from a “target”; or the depth of penetration of the radar; or velocity; or average dielectric constant. The data may be displayed in three different formats:

Grey scale line-scan: this is the most common form of display. The printout looks like a fax roll.

Colour line-scan: this can be used to highlight certain features.

Single wiggle-plot: this can be used to enable detail examination of a single radar pulse in order to examine one single feature.

Figs. 1 and 2 illustrate radar representational outputs.

D.3.11 TEST REPORT

1. A reference to this RILEM Standard
2. The date of the test
3. Description of the testing conditions, *e.g.*, site, geo-

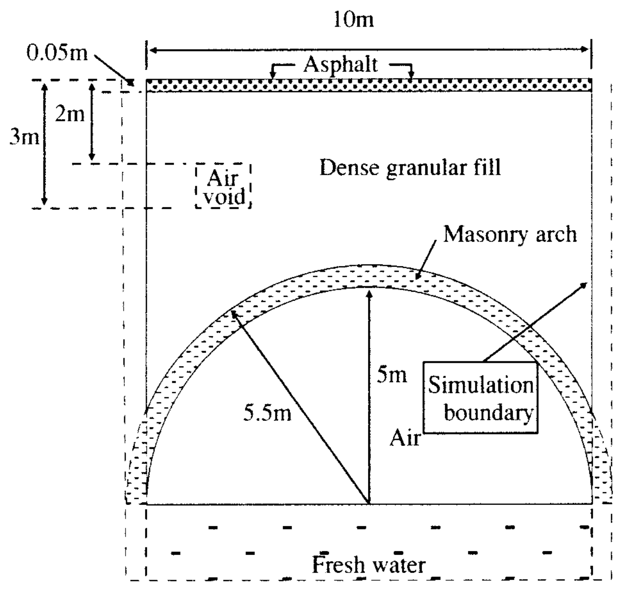

Fig. 1a – Masonry arch bridge: section through bridge showing single rectangular void in homogeneous dense granular soil fill.

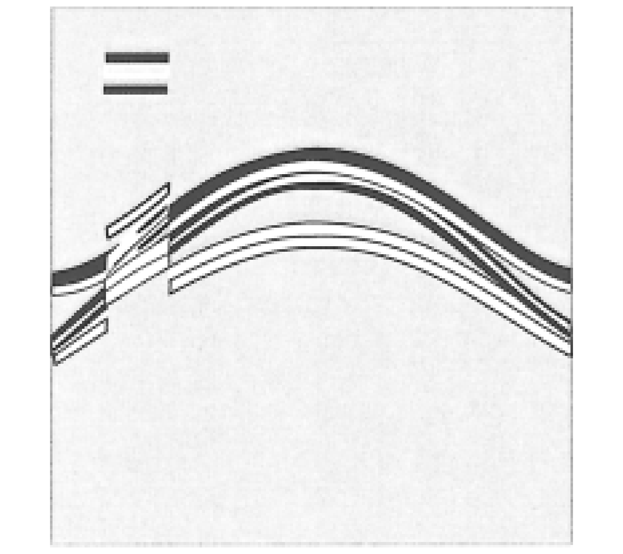

Fig. 1b – Masonry arch bridge: Line scan (redrawn for clarity) of bridge with voided fill.

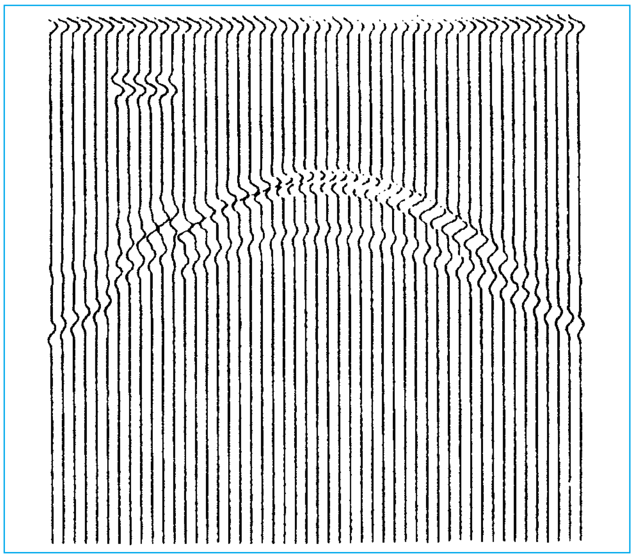

Fig. 1c – Masonry arch bridge: Wiggle plot of bridge with voided fill.

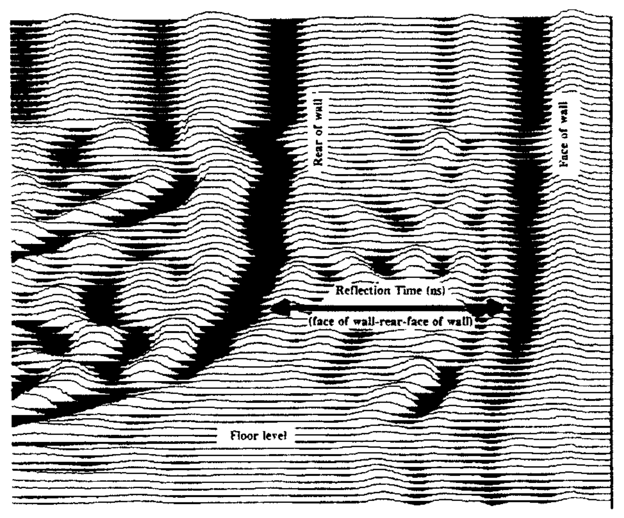

Fig. 2 – Radar line scan showing capillary rise in masonry.

graphical location, environmental conditions, temperature, building identification, date of construction (if available), and name of the technician conducting the test. Include details of the type and quality of construction.

4. Type and model of equipment used including date of most recent calibration.

5. Identity and description of the specific test locations on the structure, including a diagram of the structural element tested, adjacent masonry, and all relevant dimensions.

6. Test results compiled in the form of chart recorder print-out; full colour ink-jet plot, 3-D interpretive model, 2-D interpretive model; other tabulation as appropriate .

7. Results from any companion destructive or in-situ tests which were conducted for calibration purposes.

D.3.12 INTERPRETATION OF TEST RESULTS

The electromagnetic radar signal will transmit through non-conductive media at high speed, but will have very limited or zero penetration through conductors. For example radar will not penetrate through metals, nor will it penetrate through sea water. However, excellent reflections will be achieved from conductors.

If one is looking for layer changes in masonry structures, then a grey scale or suitably chosen set of colour scales might be appropriate in order to identify the time to reflection [5-7] - Fig. 1. This can be converted to depth if the dielectric constant is known - the latter can be calculated using the transmission test described above or using the WARR technique (wide angle reflection and refraction).

The time reflection technique can be used very effectively to identify capillary rise in buildings - where the moisture content increases the velocity of propagation of the radar wave will reduce and it will take longer to reach the rear face - Fig. 2. This gives a very clear result as shown in [8].

If a cross-sectional image of the structure is required then complex cross-shooting of the radar impulses will be required [9].

The dielectric constant can be used as a measure of moisture content in the case of masonry arch bridges where the structure is back-filled with granular soil such as sand:

e_r = dielectric constant = 4 for dry sand, back-filled bridge
e_r = dielectric constant = 20 for wet sand, back-filled bridge.

Thus impulse radar transmission tests can be seen as a powerful investigative tool for masonry structures bridges.

D.3.13 REFERENCES

[1] Colla, C., Forde, M. C., McCann, D. M. and Das, P. C., 'Investigation of masonry arch bridges using non-contacting NDT', Proc. 6th Int. Conf. Structural Faults and Repair-95, London, July 1995, Vol I, Engineering Technics Press, 235- 239.

[2] Colla, C., Das, P. C., McCann, D. M. and Forde, M. C., 'Investigation of stone masonry bridges using sonics, electromagnetics and impulse radar', Proc. Intnl. Symp. Non-Destructive Testing in Civil Engineering (NDT-CE), BAM, Berlin, Germany, September 1995, Vol I, 629-636.

[3] Padaratz, L. J. and Forde, M. C., 'Influence of antenna frequency on impulse radar surveys of concrete structures', Proc. Int. Conf. Structural Faults and Repair-95, London, July 1995, Vol. 2, Engineering Technics Press, 331-336.

[4] Padaratz, L. J. and Forde, M. C., 'A theoretical evaluation of impulse radar wave propagation through concrete', *J. Non-destructive Testing and Evaluation* **12** (1995) 9-32.

[5] McCavitt, N. and Forde, M. C., 'Numerical simulation of impulse radar through masonry', Proc. Int. Conf. Structural Faults and Repair-93, University of Edinburgh, June 1993, Vol. 3, Engineering Technics Press, 289-296.

[6] Forde, M. C. and McCavitt, N., 'Impulse radar testing of structures', Proc. Instn Civ Engrs Structs and Bldgs, 99, Feb. 1993, 96-99.

[7] Fairfield, C. A., Sibbald, A. and Forde, M. C., 'Radar measurements of density variations around an arch bridge', Br. J. NDT, Nov 1995.

[8] Binda, L., Colla, C. and Forde, M. C., 'Identification of moisture capillarity in masonry using digital impulse radar', *J. Construction and Building Materials* **8** (2) (1994) 101-107.

[9] Schuller, M., Berra, M., Atkinson, R. and Binda, L., 'Acoustic tomography for evaluation of unreinforced masonry', Proc. Int. Conf. Structural Faults and Repair-95, London, July 1995, Vol. 3, Engineering Technics Press, 195-200.

Category D:
In-situ and non-destructive test proposed test method

MS.D.4: MEASUREMENT OF LOCAL DYNAMIC BEHAVIOUR FOR MASONRY

D.4.1 CONTENTS

D.4.2 SCOPE

This recommendation specifies a method for determining the dynamic behaviour of masonry structures using low frequency mechanical impulse techniques. Details regarding the principles involved, the apparatus, the method of test, the method of calculation and the contents of the test report are provided. The impulses (stress waves) are induced by striking the masonry with an instrumented hammer with built-in load cell, monitoring the response using an accelerometer, recording the data on a simultaneous two-channel FFT analyser with built-in front end analogue and digital anti-aliaising filters.

D.4.3 BACKGROUND

Historic structures such as cathedrals and masonry arch bridges and many, more modern, buildings often lack accurate or perhaps any drawings of their construction. Considerable problems occur when it becomes necessary to assess the structural stability of a critical component of a complex structure. Examples include: multi-wythe bell towers of churches, the condition and degree of bonding between arch rings in brick masonry bridges, the degree of attachment of masonry facing walls to rockfaces or retaining walls and the support status of panels in high-rise structures. Thus non-invasive techniques such as dynamic stiffness have a growing role.

D.4.4 SITE APPLICATION OF THE TEST

The dynamic stiffness test can be used to determine:
– stiffness of the structure
– voiding behind a wall
– cracks
– major defects
– delamination
– debonding of facades.

D.4.5 TEST LOCATIONS

Test locations are dictated by engineering objectives, however an attempt should be made to measure the variation in material quality or condition throughout the structure. The number of tests required is dependent upon the accuracy and resolution desired in the evaluation. A quick survey of material uniformity may require only a few tests in each area of interest, whereas an in-depth analysis will require a dense grid-work of tests. Generally, a large number of replications are required to provide a reliable statistical database. The level of replication required depends on the variability of the test results. It will be normal practice to test a matrix grid of points and then evaluate the dynamic stiffnesses obtained using a pseudo 3-D type plot or a contour plot - commercial software is readily available. An appropriate first mapping matrix might be at 1 metre centres.

D.4.6 PRINCIPLE OF TEST

The dynamic stiffness of a masonry structure will increase with the "quality" of the structure and decrease as the "quality" of the structure degrades. Thus if a portion of a structure is voided or lacks mortar then the local dynamic stiffness of the structure will decrease. Also in the case of panel walls the dynamic stiffness of the wall will vary across the wall due to the fixity of the panel and the density and efficiency of any tying. The dynamic stiffness will change smoothly across the structure from top to bottom and transversely from side to side - the minimum stiffness will be in the zone subject to boundary conditions. Any anomaly in the pattern of change will indicate a variation in the quality of the structure. This is best interpreted from either a pseudo three-dimensional plot or a stress contour plot.

The basic principle behind the test is that time domain signals are recorded from both a load cell contained within a modally tuned hammer and an accelerometer mounted on the structure. The simultaneous signals, having been filtered using anti aliaising filters, are then transformed to the frequency domain using a fast Fourier transform (FFT) algorithm. The output (from the accelerometer) is divided by the input (from the load cell in the hammer) to yield the frequency response function (FRF). The dynamic stiffness is measured from the initial portion of the frequency response function plotted on a log-log plot in the form of a dB vertical scale and logarithmic horizontal frequency axis - Fig. 1. This technique of calculating dynamic stiffness from the initial portion of the frequency response function is well established modal testing practice in mechanical and aeronautical engineering.

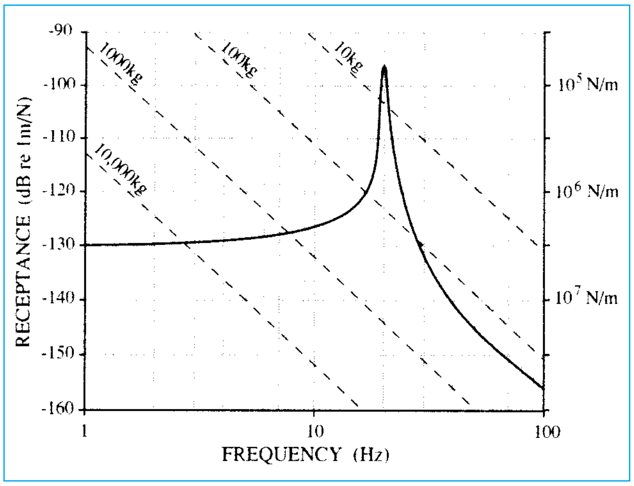

Fig. 1 – Measurement of Dynamic stiffness: Log-log receptance plot for undamped SDOF system.

D.4.7 CONDITIONS OF TESTING

Tests should be conducted under steady state ambient conditions, however the work should not be carried out in heavy rain or other conditions likely to cause serious fluctuations in the state of specimens or the instrumentation. An example of this would be in periods of rapidly changing temperatures due to varying sunlight conditions. Ideally, the test should be undertaken over a short time span in the absence of direct sunlight if this were practicable.

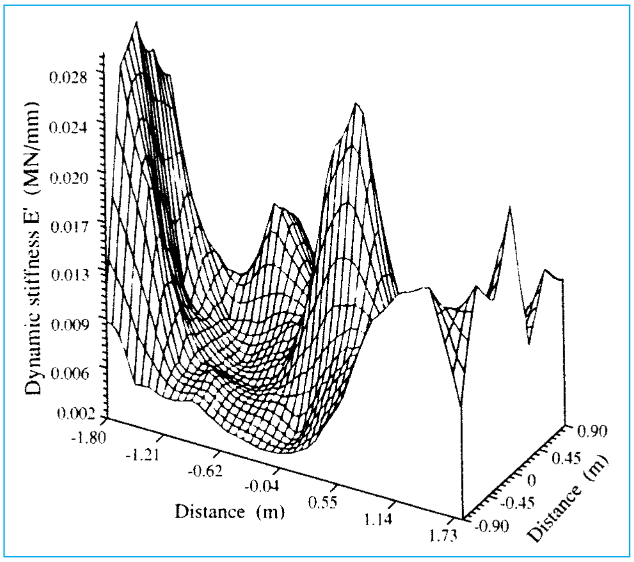

Fig. 2 – 3-D plot: Dynamic stiffness of intact slab with a 45% underlying void.

D.4.8 APPARATUS

The equipment required includes:

– an instrumented hammer with built-in load cell adjacent to the plastic/metal modally tuned tip. Note that the frequency of the tip is limited by the hardness of the surface. For example a metal tipped hammer would cause the surface of stone masonry to crumble – a similar problem has been observed on concrete [1, 2].

– an accelerometer giving linear response from D.C. to 1 kHz; the sensitivity of the accelerometer may be between 100 mV/g and 1000 mV/g.

– simultaneous sampling two channel FFT analyser with built-in anti-aliasing filters and minimum of 12-bit analogue to digital converter with minimum 60 dB dynamic range. It is unacceptable for the work to be undertaken using a computer with a built-in analogue to digital card multiplexing and with no anti-aliasing filters. Multiplexing will give rise to phase errors. Lack of anti-aliasing filters may give rise to spurious apparent low frequency aliasing errors.

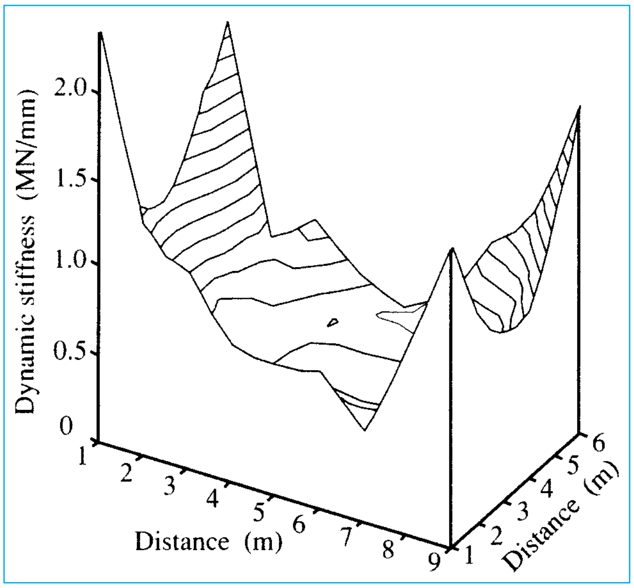

Fig. 3 – Mode shape of a masonry bridge (Second arch condition - before load applied).

D.4.9 PROCEDURE

First the points to be tested should be marked out at carefully measured positions on the masonry wall. Ideally these should be on a grid pattern matrix – 1 metre grid would be an appropriate first choice.

At each test point the accelerometer should be carefully mounted using a thin layer of bees wax or a similar acoustic couplant. The trigger level should be set on the two-channel FFT analyser; a frequency span of D.C. – 2 kHz would be appropriate. The structure should then be struck and the signal recorded. The data should be recorded digitally either directly into the analyser using bubble memory, built-in floppy disk drive or externally to a computer disk drive (preferably using an IEEE bus).

Cautionary note: Before calculating the frequency response function (FRF) and then the dynamic stiffness, (E'), as outlined above, the time domain hammer signal and the time domain accelerometer responses should be inspected to ensure that a clean hammer blow has been achieved and that a good response has been achieved by the acoustic couplant. It is possible that if the masonry has been chipped then a clean hammer blow will not have been obtained and the accelerometer response will show high frequency "spikes". A further potential problem is that if the gain settings on the FFT analyser have been incorrectly set, then the amplitude of the signal obtained will be too low and thus the signal to noise ratio will be too low. Another problem is that if the sensitivity is set to too great a gain then the hammer load cell may be overloaded and a poor quality time domain signal recorded. This would result in an erroneous calculation of dynamic stiffness.

D.4.10 TEST RESULTS

The result should be calculated as in Fig. 1 and expressed as dynamic stiffness, E', in units of MN/mm.

The data should preferably then be plotted as the matrix of points to give a contour plot or pseudo three-dimensional stiffness plot - Fig. 2 [3]. An alternative strategy would be to look at mode shapes of the structure [4] - Fig. 3.

D.4.11 TEST REPORT

1. A reference to this RILEM standard.
2. The date of the test.
3. Description of the testing conditions *e.g.* site, geographical location, environmental conditions, temperature, building identification, date of construction (if available) and name of technician conducting the test.
4. Include details of the type and quality of construction.
5. Type and model of equipment used, including dates of most recent calibration.
6. Diagram giving identity and description of the sonic test locations on the structure.
7. Test results compiled in tabular format, contour plot and pseudo 3-D plot as appropriate.
8. Results from any companion destructive or in-situ tests which were conducted including any correlations with other types of test.

D.4.12 INTERPRETATION OF TEST RESULTS

The interpretation of the results can be in one of two forms:

1. Dynamic stiffness contour plots: this is the most common approach [3] where the higher is the dynamic stiffness, the less is there a likelihood of a void. This must be qualified by the consideration that in a panel structure high edge stiffness will represent fixity at the edges.
2. Mode shapes: these can be used for relative changes in quality [4]. However this technique can only be used if there is a basis for comparison between good-and bad.

References [5-9] give further reading on the interpretation of the techniques.

D.4.13 REFERENCES

[1] Martin, J. and Forde, M .C., 'Influence of concrete properties on impulse hammer spectrum and compression wave velocity', *J. Construction and Building Materials* **9** (4) (1995) 245-255

[2] Martin, J., Hardy, M. S. A., Usmani, A. S. and Forde M. C., 'Influence of impulse spectrum on defect detection in post tensioned bridges', Proc. Intnl. Symp. Non-Destructive Testing in Civil Engineering (NDT-CE), BAM, Berlin, Germany, Vol 2, September, 1995, 789-796.

[3] McCavitt, N., Yates, M. R. and Forde, M. C., 'Dynamic stiffness analysis of concrete pavement slabs', *ASCE J. Transportation Engng* **118** (4) (Jul/Aug 1992) 540-556.

[4] Forde, M. C. and McCavitt, N., 'Sonic NDT and radar testing of masonry', *Br. J. NDT* **36** (3) (Mar. 1994) 140-147.

[5] Schuller, M., Berra, M., Atkinson, R. and Binda, L., 'Acoustic tomography for evaluation of unreinforced masonry', Proc. Int. Conf. Structural Faults and Repair-95, Vol. 3, London, July 1995, Engineering Technics Press, 195-200.

[6] Birjandi, F. K. and Forde, M. C., 'Sonic and ultrasonic testing of stone masonry', *Masonry International* **5** (3) (1992) 79-82.

[7] Sibbald, A., Fairfield, C. A. and Forde, M. C., 'Impulse testing of brickwork sewers', *J. Low Frequency Noise and Vibration* **14** (1) (1995) 43-54.

[8] Armstrong, D. M., Sibbald, A. and Forde, M. C., 'Integrity assessment of masonry arch bridges using the dynamic stiffness technique', NDT and E International, Dec 1995

[9] Forde, M. C., Invited Keynote Paper: 'Non-destructive evaluation of masonry bridges', Proc. 2nd Int. Conf. on Nondestructive Testing of Civil Structures and Materials, University of Colorado, Boulder, 17-42, May 1992.

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Category D:
In-situ and non-destructive test proposed test method

MS.D.8: ELECTRICAL CONDUCTIVITY INVESTIGATION OF MASONRY

D.8.1 CONTENTS

D.8.2 SCOPE

This recommendation specifies a method for investigating electrical conductivity distribution within masonry structures using electro-magnetic conductivity techniques. Electromagnetic fields are propagated into the structure and variations are monitored and recorded. These provide geometrical and electrical information on the materials investigated. Details regarding the principles involved, the apparatus, the method of test, the method of calculation and the contents of the test report are provided.

D.8.3 BACKGROUND TO THE TEST

Water ingress and moisture movement into structures are 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 [1]. 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 what shows on the external wall surface [2].

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 would be of great engineering value.

Electrical conductivity in porous building materials as a response to electrical fields over the range from DC to 20 kHz AC is influenced to a large extent by the content of moisture and soluble ionic salts and thus offers a relevant ND assessment technique for the following:
– 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 inhomogeneities in the wall
– presence of metal reinforcements, pipes, drains etc. in the wall.

D.8.4 TEST LOCATIONS

Test locations are dictated by engineering objectives, however an attempt should be made to measure the variation in material quality or condition throughout the largest possible volume of the structure [3] – typically that with a face area of 3m x 3m minimum. From such a large map of the conductivity distribution in the sub surface, it should be possible to identify the area of interest.

Since no coupling or contact with the surface of the structure is required, the surface of the structure remains unmarked. As a result of the portability of the instrument, the non-harmful nature of the radiation and the continuous emission and receptivity of electromagnetic fields, the structure can be tested rapidly, safely and without disruption of other activities.

As the in-situ calibration is of great importance in the interpretation of the readings obtained, it is recommended that, if conductivity surveys have to be repeated over a period of time, calibration settings should be recorded so that they can be exactly reproduced. Thus measurements taken on different dates can be compared for structural condition monitoring.

It is normal procedure to test the structure along survey lines either longitudinally or vertically, thus a series of traverse or reading stations should be marked out for investigation.

The number of readings required is dependent upon:

– the accuracy and resolution required in the evaluation,
– upon the instrument used,
– the operating mode of use of the equipment itself.

D.8.5 PRINCIPLE OF TEST

The application of this electromagnetic technique for measuring conductivity involves the use of a transmitter coil energised with an alternating current and a receiver coil located a short distance away. The time-varying magnetic field arising from the current induces very small currents in the structure. These currents generate a secondary magnetic field which is sensed, together with the primary field, by the receiver coil. The conductivity equipment permits the measurement of near surface average conductivity. It should be noted that the results are averaged over the depth of penetration.

This secondary field is a function of the inter coil spacing, the operating frequency and the conductivity of the materials, and reveals the presence of a conductor and provides information on its geometry and electrical properties [12, 13]. The induction of current flow results from the magnetic components of the EM field, consequently there is no need for physical contact with the surface of the structure investigated (Fig. 1). Typical values of conductivity for geological and building materials are given in Appendix A. Further details on principles of operation and instrumentation capabilities are contained in Appendix B.

D.8.6 CONDITIONS OF TESTING

Tests should be conducted under ambient conditions, however the work should not be carried out in heavy rain or other such adverse conditions as these will cause significant errors. Water ingression to levels approaching saturation will significantly affect the results of a conductivity survey.

D.8.7 APPARATUS

The system comprises a conductivity meter emitting continuously, and receiving electromagnetic fields through two coils. Typical commercial instruments would be operating at approximately 15 kHz for penetration depth range up to 0.75-1.5 metres. Lower operating frequency (around 10 kHz) could be used for penetration depths up to 6 metres. Conductivity meters can be operated both in vertical and horizontal mode, giving double the depth of penetration in the former mode, compared with the latter.

A digital data logger can be attached to continuously record the output from the meter. Fig. 2 illustrates the use of the equipment and data logger on a stone masonry wall.

The instrument measures conductivity using electromagnetic inductive techniques and reads directly in milliSiemens per metre. The value of the reading is a function of the conductivity of the matter between the instrument and its maximum depth of penetration - see Appendix B.

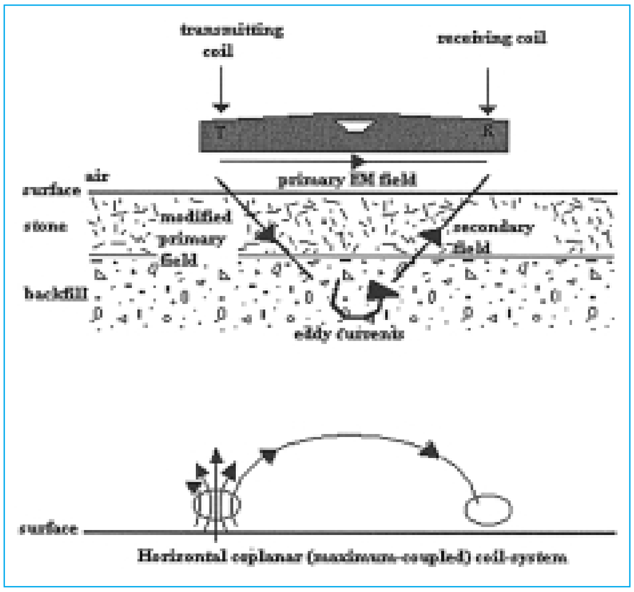

Fig. 1 – Conductivity instrument operating on masonry structure [6].

Fig. 2 – In situ conductivity data collection on stone masonry structure [6].

D.8.8 PROCEDURE

The procedure will involve marking out the masonry wall in traverses either horizontally or vertically. If the meter is to be operated in automatic mode, readings will be collected continuously along the survey lines. If the meter is operated in manual mode, stations will have to be marked on the traverses, at regular intervals related to the intercoil spacing. Minimum recommended spacing between reading stations is equal to the spacing between transmitter and receiver on the meter. A denser grid of reading points will give a better resolution in the final contour map. The lateral extent of the volume whose conductivity is sensed by the meter is approximately the same as the vertical depth.

The choice of conductivity meter depends on the dimensions of the structure to be tested and on the depth of penetration desired – see Appendix B. Quadrature-Phase and In-Phase readings are both to be collected or the surveyor can limit the readings to one of the two phases, depending on the aim of the test.

D.8.9 TEST RESULTS AND PRESENTATION

Data should be plotted so as to obtain the contour of the area investigated (Fig. 3), or pseudo three-dimensional distribution of the conductivity (Fig. 4). Plotting of conductivity values across sections of the structure is also a possibility. Commercial software is available for producing 2-D contour map plots and tomographic elaboration of the section investigated [3, 17].

There are a number of ways of elaborating and presenting the data:
– data can be plotted on to a CAD-CAM generated 3-D type plot of a structure: building or bridge as per Fig. 4 [6] or more simply superimposed on the wall drawing or image, as per Fig. 3 [6].
– using a tomographic analysis the thickness of the stone walls can be estimated [4, 5].

D.8.10 TEST REPORT

The test report should:
1. include a reference to this RILEM standard
2. identify the location of the structure
3. give the dimensions of the structure and any available data of the materials
4. specify the size and location of the test area
5. identify and plot the measuring grid
6. state the make and model of conductivity meter used
7. if a non-standard meter is used, state the specifications
8. state whether vertical or horizontal mode is used
9. give the date and weather conditions (possibly temperature) during test
10. plot the results in tabular format or graphical format
11. give the results of any complementary tests.

D.8.11 INTERPRETATION OF RESULTS

The results can be used for a number of purposes:
– to identify changing moisture content profiles over a masonry building or bridge at a single point in time

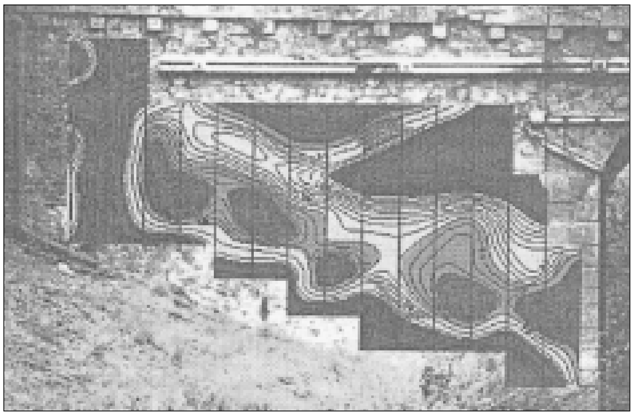

Fig. 3 – Conductivity distribution on wall of masonry structure for measurement depths up to 1.5 m [6].

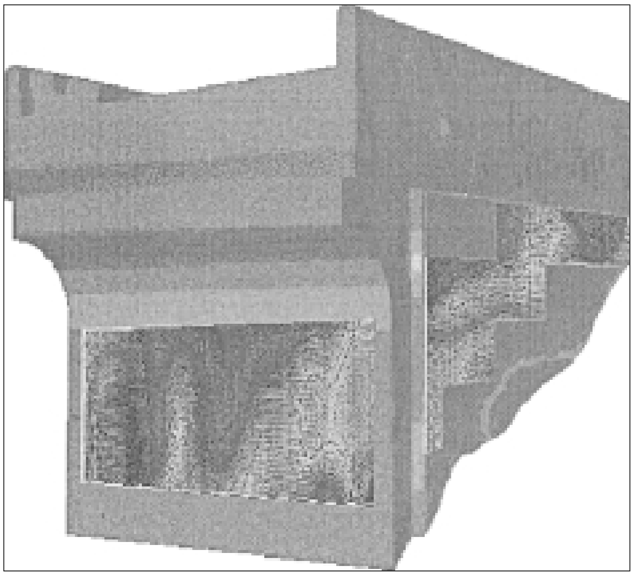

Fig. 4 – Conductivity distribution on upstream wingwall and abutment wall [6].

– to identify moisture content variations over time at identical locations on the structure.
– for detecting whether the section or element investigated is damp
– for indications whether a radar survey on the same structure could be successful depending on the material conductivity value [6].

In all cases it is advised that the results are calibrated against some physical measurement on the structure – such as a core hole or data from simple mixture content tests such as the drilling method [X].

D.8.12 REFERENCES

[1] Colla, C, Forde, M. C., McCann, D. M. and Das, P. C., 'Investigation of masonry arch bridges using non-contacting NDT', Proc. 6th Int. Conf. Structural Faults and Repair-95, London, July 1995, Vol. 1, Engineering Technics Press, 235-239.
[2] Binda, L., Colla, C. and Forde, M. C., 'Identification of moisture capillarity in masonry using digital impulse radar', *J. Construction and Building Materials* **8** (2) (1994) 101-107.
[3] Colla, C., Das, P. C., McCann, D. M. and Forde, M. C., 'Investigation of stone masonry bridges using sonics, electromag-

netics and impulse radar', Proc. Int. Symp. Non-Destructive Testing in Civil Engineering (NDT-CE), BAM, Berlin, Germany, September 1995, Vol. 1, 629-636.
[4] Colla, C., McCann, D. C., Das, P. G. and Forde, M. C., 'Non contact NDE of masonry structures and bridges', Proc. 3rd Nondestructive Evaluation of Civil Structures and Materials, Boulder, Colorado, USA, 1996.
[5] Colla, C., McCann, D., Das, P. and Forde, M. C., 'Investigation of a stone masonry bridge using electromagnetics, Evaluation and strengthening of existing masonry structures', (Binda, L., Modena, C., eds.), RILEM, 1997, p.163-172.
[6] Colla, C., 'NDT of masonry arch bridges', PhD Thesis, The University of Edinburgh, Dept. Civil and Environmental Engineering, Edinburgh, 1997, 242 pp.
[7] Culley, R. W., Jagodits, F. L. and Middleton, R. S., 'E-phase system for detection of buried granular deposits', Symposium on Modern Innovations in Subsurface Explorations, 54th Annual Meeting of Transportation Research Board, 1975.
[8] Davidson, N. C., Forde, M. C., 'A laboratory appraisal of ground-penetrating radar over water', *Nondestructive Testing and Evaluation* **12** (4) (1996) 219-242.
[9] Heiland, C. A., 'Geophysical exploration', New York, Hafner Publishing Co. 1968.
[10] Kearey, P. and Brooks, M., 'An Introduction to Geophysical Exploration', Oxford, 1991.
[11] Keller, G. V. and Frischknecht, F. C., 'Electrical methods in geophysical prospecting', Ch. 1. Pergamon Press, N.Y., 1966.
[12] McNeill, J. D., 'Electrical conductivity of soils and rocks', Ontario, Geonics Limited, Technical Note TN-5, 1980, 22 pp.
[13] McNeill, J. D., 'Electromagnetic terrain conductivity measurement at low induction numbers', Ontario, Geonics Limited, Technical Note TN-6, 1980, 15 pp.
[14] Milsom, J., 'Field Geophysics', Geological Society of London Handbook, 1989, 182 p.
[15] Olhoeft, G. R., 'Electrical properties of rocks. The physics and chemistry of rocks and minerals', J. Wiley and Sons, N.Y., 1975, p. 261-278.
[16] Olhoeft, G. R., 'Electrical properties of natural clay permafrost', *Can J. Earth Science* **15** (1977) 16-24.
[17] Schuller, M., Berra, M., Atkinson, R. and Binda, L., 'Acoustic tomography for evaluation of unreinforced masonry', Proc. Int. Conf. Structural Faults and Repair-95, London, July 1995, Vol. 3, Engineering Technics Press, 195-200.
[18] Sellmann, P. V., Delaney, A. J. and Arcone, S. A., 'Observations of radar performance for bottom and sub-bottom information in fresh water', Proc. 2nd Government Workshop on GPR, Advanced Ground-Penetrating Radar: Technologies and Applications, Ohio State University, 26-28 Oct. 1993, p. 59-70.
[19] Smith-Rose, R. L., 'Electrical measurements on soil with alternating currents', *Proc. IEE* **75** (1934) 221-237.
[20] Stewart, R. D., Anderson, W. L., Grover, T. P. and Labson, V. F., 'Shallow subsurface mapping by electromagnetic sounding in the 300 kHz to 30 MHz range: model studies and phototype system assessment', *Geophysics* **59** (8) 1994, 1201-1210.
[21] Tamas, F., 'Electrical conductivity of cement pastes', *Cement and Concrete Research* **12** (982) 115-120.
[22] Telford, W. M., Geldart, L. P., Sheriff, R. E. and Keys, D. A., 'Applied Geophysics', Ch. 5, Cambridge University Press, N.Y., 1976.
[23] Ward, S. H. and Fraser, D. C., 'Conduction of electricity in rocks', Ch. 2. Mining Geophysics, Soc. of Exploration Geophysicists, Tulsa, Oklahoma, vol. 2, 1967.
[24] Woods, R. D. (ed.), 'Geophysical characterisation of sites', Rotterdam, A. A. Balkema, 1994, 141 pp.

APPENDIX A – TYPICAL VALUES OF CONDUCTIVITY FOR BUILDING MATERIALS

A.1 Definition of conductivity

The reciprocal of the electrical resistivity is defined as the electrical conductivity, a measure of the ease with which an electrical current can be made to flow through a substance. In the MKS system the unit of conductivity is the mho per meter – or Siemen per meter – and a resistivity of one ohm-meter (1 Wm) exhibits a conductivity of one mho per meter (1 w/m) or one Siemen per meter (1 S/m). For convenience, conductivity values are usually defined in milliSiemens per meter (mS/m).

A.2 Factors affecting the conductivity

Values of conductivity are usually recorded when direct current is employed for the measurements but it must be noted that the electrical properties of the sample may vary with the instrumentation frequency [11, 15, 16, 23].

For materials with conductivity between 1 and 1000 mS/m the electrical properties which control the current flow are relatively independent of frequency and the DC or low frequency conductivity measured with conventional resistivity and conductivity equipment will essentially be the same as that measured using low frequency (up to 300 kHz) electromagnetic techniques [12].

Most soil and rock minerals forming building materials are insulators and conduction through the rock matrix only takes place when certain clay materials, native metals and graphite are present [9, 20, 24]. The minerals in the sand and silt fractions of the soil are electrically neutral and are generally excellent insulators. The electrical conductivity of the material is thus primarily controlled by the particle size, the amount of water present in the pores and by the conductivity of the pore fluid. The general trend is that conductivity will increase with reducing particle size, increasing moisture content and increasing salt content.

Measurements made on material as a function of the moisture content by weight, show a conductivity that increases approximately as the square of the moisture content [19].

The solutions of salts in pore water will substantially increase the material conductivity [6, 12].

The temperature dependence of the electrical conductivity of the electrolyte is almost entirely due to the temperature dependence of the viscosity of the liquid and a change in conductivity of 2.2% per degree may be expected. This phenomenon implies that for high seasonal changes of temperature, the conductivity over the normal range of ambient temperature may double.

Unconsolidated materials at temperate ambient temperatures usually display a range of conductivity between 1 and 1000 mS/m, whilst the conductivity of rocks lies between 0.01 mS/m and 100-200 mS/m. The conductivity of masonry structures and walls made up of natural

Table A.1 – Typical values of conductivity for geological and building materials

Material Type	Conductivity range (mS/m)	Reference
Sandstone masonry	0.1 - 140	Colla, 1997
Conglomerates	0.1 - 2	Telford *et al.*, 1976
Sandstones	6.4 x 10-5 - 1	Telford *et al.*, 1976
Sandstones	0.1 - 300	Culley *et al.*, 1975
Limestones	10 -4 - 500	Telford *et al.*, 1976
Limestones	5 - 700	Culley *et al.*, 1975
Loose sand	0.01 - 1	Culley *et al.*, 1975
Alluvium and sands	80 - 100	Telford *et al.*., 1976
River sand and gravel	7 - 10	Culley *et al.*, 1975
Clays	10 - 1000	Telford *et al.*, 1976
Argillites	80 - 100	Telford *et al.*, 1976
Top soil	30 - 700	Culley *et al.*, 1975

building materials can be expected to be in a range between 0 and 150 mS/m.

Measuring the conductivity of water is a valuable information when a GPR radar survey is to be carried out over fresh or polluted water for bottom and sub-bottom investigation. The value will give an indication on the radar signal penetration [8, 18]. Other examples of applications of conductivity measurements include monitoring concrete curing and decay process [21].

Table A.1 gives a broad indication of the conductivity of geological and building materials but extreme caution must be exercised in employing these values for anything than a rough guide.

APPENDIX B – EQUIPMENT

B.1 Principles of instrumentation operation

A transmitter coil Tx energised with an alternating current at an audio frequency is placed on the material or structure surface and a receiver coil Rx is located a short distance *s* away. The magnetic field arising from the alternating current in the transmitting coil induces very small currents in the structure material. These currents generate a secondary magnetic field Hs which is sensed, together with the primary magnetic field Hp, by the receiver coil (Fig. 1). The response fields differ both in phase and amplitude from the transmitted ones, and these differences reveal the presence of the conductor and provide information on its geometry and electrical properties.

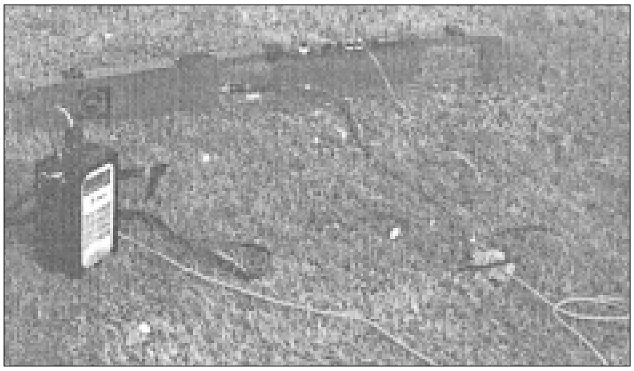

Fig. B.1 - EM 38 Geonics conductivity meter and data logger (by permission of Geonics Limited).

In general this secondary magnetic field is a function of the intercoil spacing *s*, the operating frequency *f* and the conductivity σ and, at low induction frequency, it is shown to be:

$$\frac{H_s}{H_p} \cong \frac{i\omega\mu_o\sigma s^2}{4}$$

where H_s = secondary magnetic field at the receiver coil
H_p = primary magnetic field at the receiver coil
ω = 2pf
f = frequency (Hz)
μ_o = permeability of free space
σ = ground conductivity (S/m)
s = intercoil spacing (m)
i = √-1.

The ratio of the secondary to the primary magnetic field is therefore linearly proportional to the material conductivity.

Given a frequency and an intercoil spacing, a maximum depth of penetration can be reached. For example, at a frequency of 14.6 kHz and intercoil spacing of 1 metre, a maximum depth of penetration of 1.5 m can be reached. This depth of exploration is generally considered suitable for masonry structure investigation, including historical ones. The Geonics EM 38 (Fig. B.1) is one of such instruments commercially available but, provided that the operating frequency and intercoil spacing are similar to the figures previously quoted, any other conductivity meter could be used. The lower the frequency, the deeper the penetration but the poorer the resolution - as amplitude decreases exponentially with depth [10, 14].

The value of conductivity read on the instrument does not represent the conductivity at any particular depth, rather the value is a function of all the matter between the face of the instrument and the maximum depth of exploration. This function is represented in Fig. B.2 for the horizontal and vertical modes of operation of the instrument and expressed by f_H and f_V respectively.

The instrument can be rolled over so that the vertical dipole transmitter/receiver geometry becomes a horizontal dipole transmitter/receiver geometry. This feature is useful in diagnosing and defining a layered media. Changing the conductivity of any one of the layers of a horizontally stratified structure, such as a multi-wythe masonry wall or masonry arch bridge abutments, spandrel and wing walls, will not alter the geometry of the current flow. Varying the conductivity of any layer will proportionally vary only the magnitude of the current in that layer. To calculate the resultant magnetic field at the surface it is simply necessary to calculate the independent contribution from each layer, which is a function of

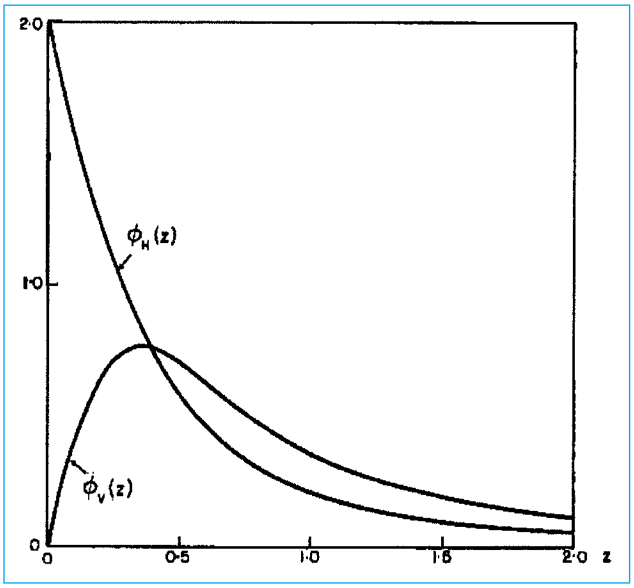

Fig. B.2 - Comparison of relative responses for vertical and horizontal dipole modes of instrument operation in function of depth [13].

its depth and conductivity, and to sum all the contributions. The technique allows this calculation due to its non-contacting characteristic mode of operation. Consequently, the instrument can be lifted off the surface of the structure and readings can be taken at increasing distances from the wall surface.

APPENDIX C – EXAMPLE OF CONDUCTIVITY MEASUREMENTS ON MASONRY STRUCTURE

An example of conductivity survey on masonry structure is reported below for the case of a stone masonry arch bridge. The work is extensively reported in [4-6].

The meter used has inter-coil spacing of 1m and provides a maximum depth of exploration of 1.5 m in Vertical Dipole Mode (0.75 m in Horizontal Mode) operating at a frequency of 14.6 kHz.

The meter has been used on both the upstream and downstream sides of this 2-span bridge and on one abutment wall beneath the main vault. The measurement stations followed a grid marked on the walls, in an area well clear of any evident metallic objects (drains, reinforcing beams). For maximum accuracy and good spatial resolution, measurements have been overlapped to have reading stations every half a meter. The lateral extent of the volume of structure whose conductivity is sensed, permits accurate measurement of small changes in conductivity, for example of the order of 5% or 10%. Contacting and non-contacting – at 0.25, 0.5 and 0.75, 0.9 m distance from the wall surface – conductivity measurements were taken, to obtain data at different depths inside the structure. Data were collected in a digital data recorder and later transferred to a PC for elaboration and presentation in 2D contour maps and section plots.

The values obtained are in a high and very wide range: conductivity readings registered were as high as 120 mS/m. The highest values were recorded on the downstream side with an average of 60 mS/m, and the lowest on the abutment wall (average of 38 mS/m), whilst the upstream side registered an average conductivity value of 40 mS/m.

Such values are indicating heterogeneity in soil filling in the abutment, variations in moisture content and salinity.

The results have been plotted to produce contour maps of the conductivity distribution along horizontal and vertical planes within the structure. Fig. C.1 is the plot of the conductivity data obtained on a vertical plane of the abutment wall for depth up to 1.5 m from the external surface.

Surveys were repeated over a period of months and differences were noticed, in particular behind the wall under the vault. Comparison of results from data taken with maximum depth of exploration (1.5 m) lead to the hypothesis that a significant moisture/water movement is taking place in an area at the rear face of that wall with concern about the possible loss of the fine part of the filling; this hypothesis was reinforced by the low velocity values obtained from sonic tomography in that same area.

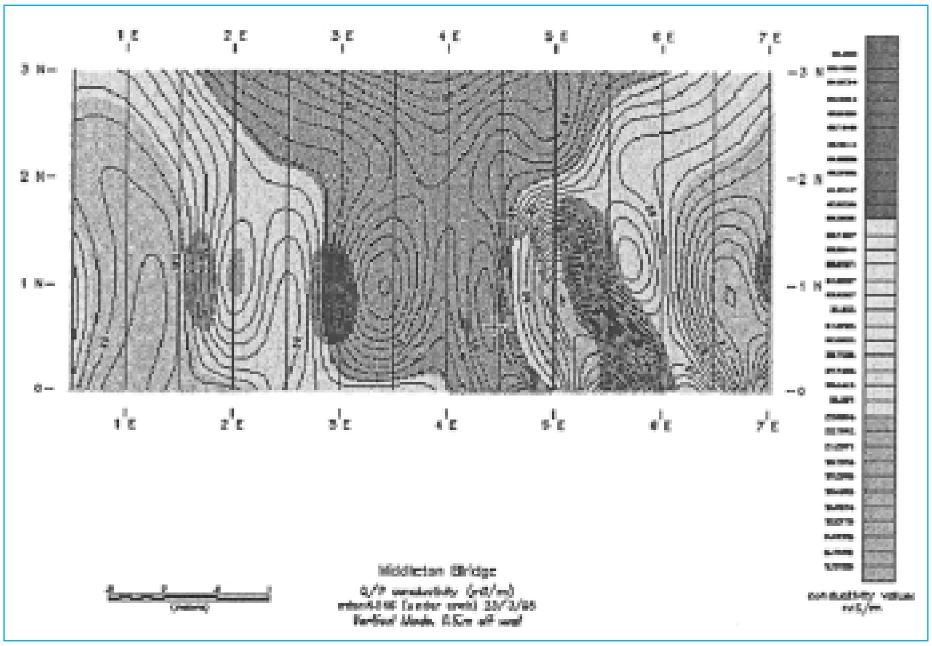

Fig. C.1 – Conductivity distribution on abutment wall [4].