NON DESTRUCTIVE
TEST METHODS OF STONE AND ROCK

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Summary

This report contains an over-view of geophysical and civil engineering non-destructive test methods, which may be applied to the study of stone and rock. Mechanical and electrical methods are presented and their technical and economical feasibility are estimated. The mechanical methods contain the seismic, ultrasonic, hammer and the acoustic emission methods. The electrical methods are the radar, resistivity and the electromagnetic methods.

CONTENTS

NOTIONS

Latin symbols

A	cross section area	m^2	
c	speed of mechanical wave, wave velocity	m/s	
c	speed of light in vacuum	m/s	
c_L	speed of L-waves	m/s	
c_m	speed of light in a medium	m/s	
c_P	speed of P-waves	m/s	
c_R	speed of R-waves	m/s	
c_S	speed of S-waves	m/s	
e	mathematical constant = 2.718		
f	frequency	Hz, cycles/s, Hertz	
f_0	natural frequency	Hz, cycles/s, Hertz	
G	shear modulus	N/m^2	
H	thickness of a layer	m	
I	electrical current	A	Ampére
L	length	m	
ΔL	distance	m	
n	exponential in geometrical attenuation		
n	number of reflections		
Q	goodness number of internal damping		
r	distance	m	
R	electrical resistance	Ω	Ohm
R	reflection coefficient		
T	travel time	s	
ΔT	time difference	s	
$u(r, t)$	displacement as function of distance and time	m	
$\hat{u}(r)$	displacement amplitude as function of distance	m	
U	electrical potential	V	Volt
x	distance	m	
x^*	breaking point in refraction seismics	m	
z	specific impedance	Ns/m^3	

Greek symbols

α	constant of internal attenuation	1/m	Neper/m
$\Delta\phi$	difference in phase angle	radians	

$\Delta\theta$	difference in phase angle	cycles	
ε_r	constant of relative dielectricity		
ϕ	angle	radians	
λ	wave length	m	
π	mathematical constant = 3.142		
ρ	density (total)	kg/m^3	
ρ	electrical resistivity	Ωm	Ohm-meter
σ	electrical conductivity	S/m	Siemens/m
θ_i	angle of incidence	radians	
θ_{refl}	angle of reflection	radians	
θ_{refr}	angle of refraction	radians	

Prefixes for powers of ten

G	giga	10^9	billion
M	mega	10^6	million
k	kilo	10^3	thousand
m	milli	10^{-3}	thousandth
μ	mikro	10^{-6}	millionth
n	nano	10^{-9}	billionth

1. INTRODUCTION

The purpose of this report is to present common geophysical and civil engineering NDT methods and to describe their application to stone and to assess their potential of application. The great difference between the methods used in geophysics and civil engineering lies in the difference in geometrical scales. In geophysics the characteristic distances are kms to thousands of kms. In civil engineering the characteristic distances are tens of meters to several kms. The methods described in this report concern *waves*, mechanical or electrical, propagating through the stone material. In order to 'see' defects in the material the lengths of the waves must be of the same order as the dimensions of the defects. This means that the wavelengths used in investigations of cultural stone must be around a few millimetres. In common geophysics the wavelengths used are of the order of meters to tens of kms.

The types of defects in stone or rock can be categorised in different ways. In this report only two types of defects are recognised; i. e. *local* defects and *global* defects. Local defects are concentrated in space with a volume of a few cubic centimetres. Global defects are distributed through the stone occupying larger volumes.

The literature in geophysical and civil engineering test methods is huge. One standard textbook in geophysical methods is Dobrin (1976). Another comprehensive work, in Swedish, is Triumf (1992), which also contains a small chapter on testing of archaeological sites. There are also several journals in this field, among them Journal of Geophysics. Recently a volume was published containing material on the SASW, geotomography, seismic refraction, ground penetrating radar, dielectric and conductivity methods, (Woods ed., 1994).

Non-destructive Testing (NDT) methods have been used for testing concrete (Wiberg, 1994). There have been some problems in applying these methods to concrete probably because of the reinforcement and the strong heterogeneity of concrete. NDT testing of masonry structures are presented in Rossi (1990).

This report is organised in two parts; one part treats mechanical methods and the other part treats electrical methods. Each part is divided in chapters comprising a set of similar methods. The individual methods are described in subchapters which all have the same disposition;

a) description of the principles of the method as used in geophysics or civil engineering, quantities measured, equipment needed, limitations and special literature

b) status of the method as commonly used in geophysics and civil engineering,

2. MECHANICAL METHODS

This chapter describes some mechanical NDT - methods. These methods have been divided into seismic, ultrasonic, hammer, acoustic emission methods. Strictly speaking the ultrasonic method, which uses ultrasonic waves, is a kind of seismic method. When applying seismic methods to cultural stone the frequencies will be so high that they will reach the ultrasonic frequencies. As the conventional ultrasonic techniques are well established they will be treated separately in this report.

Some of the seismic methods, particularly the transmission and the reflection method, are standard methods in geophysics and are used since long time. These methods have been brought to a sophisticated practice primarily by the oil prospecting companies.

The ultrasonic methods are already used for cultural stone. This is probably the only method of all methods described in this report, which is used regularly for testing cultural stone.

The literature on propagation of mechanical waves and their application to seismology and geophysics is vast. The standard work in seismology, but mathematically demanding, is Aki and Richards (1980). They use a modern way of presenting the theories. A shorter presentation of seismic waves is given by Kulhanek (1993). Graff (1975) presents in addition to waves in three dimensions even waves in rods, plates, beams, shells and other engineering elements. Unfortunately the presentation contains many errors of printing in the formulas. A mathematical presentation, in Swedish, of different kinds of waves i. e. acoustical, mechanical, electrical waves and waves in water is given by Boström (1983).

2.1 SEISMIC METHODS

Seismic methods use mechanical waves to obtain data from the tests. The seismic surface wave method is strictly speaking a seismic transmission method. In this report a seismic transmission method concerns only transmission of body waves.

Mechanical waves

Mechanical wave motion means a collective phenomenon, which moves *energy* through the material. The speed of that energy movement is the *speed of the wave* or *wave velocity*. The individual particles of the material move around their points of equilibrium and retain that position after the wave has passed. This means that the particles move with a velocity, which changes with time. The *speed of the particles* or *particle velocity* is normally in the order of mm/s and is much lower than the speed of the wave which normally is in the order of km/s. Wave motion thus does not mean transport of mass.

Mechanical waves in solid material can be of many different kinds. First there are those waves, which propagate through the bulk of the material. These are the *body waves* and can be divided into two completely different types; the *longitudinal* waves and the *transverse* waves. A longitudinal wave moves the particles parallel to the direction of propagation while a transverse wave moves the particles normal (90°) to the direction of propagation.

The longitudinal wave travels with a higher speed, c_P, than the transverse wave. It is therefore called the primary wave or the *P-wave*. The transverse wave is called the secondary wave or the *S-wave*. The speed of the S - wave, c_S, is approximately half of that of the P - wave. In Table 2.1 P-and S-wave speeds are shown for some different stone materials. The author has summarised the information given in Dobrin, (1976).

Table 2.1. P- and S-wave speeds for some rock material, from Dobrin (1976). The α-values are evaluated for 50 Hz. The α– and Q-values are explained below.

Material	c_P (m/s)	c_S (m/s)	$\alpha_P\ 10^5$ (1/m)	Q
Granite	5000 - 6000	2500 - 3300	0.21 - 0.38	9800 - 15000
Granodiorite	4780	3100	-	-
Diorite	5780	3060	0.21	12900
Gabbro	6450	3420	-	-
Basalt	5400 - 6400	2700 - 3500	0.41 (5500)	6900
Dunite	6800 - 8640	3500 - 4400	-	-
Gneiss	3500 - 7500	-	-	-
Marble	3700 - 7000	-	-	-
Sandstone	1400 - 4300	-	0.71 (4300) - 1.77 (4000)	2200 - 5100
Limestone	5900 - 6100	2800 - 3100	0.37 (6000)	7100
Anhydrite	4100	-	-	-
Shale	2100 - 3400	-	0.68 (3300) - 2.32 (2150)	3100 - 7000

Other kinds of waves travel along surfaces of discontinuities between materials. These waves are called *surface waves*. The most conspicuous discontinuity is that of the free surface between stone material and air. The waves, which travel along the free surface, may also be of two different kinds. One kind is a wave, which moves the particles in an ellipsoidal orbit where one axis of the ellipsoid is normal to the surface and the other axis is in the direction of the propagation of the surface wave. This wave is called the Rayleigh-wave, or shorter the *R-wave* after the British physicist Lord Rayleigh (1842 - 1919) who first described the wave in 1887. The speed of the R-wave, c_R, is approximately 93% of the S-wave ($c_R = 0.93 \cdot c_S$).

The other kind of surface wave moves the particles in the same plane as the free surface and normal to the direction of propagation; it is a kind of S-wave. In order to propagate such a wave the material must be inhomogeneous i. e. the speed of the S-waves must be smaller at the surface than deeper below. The wave can be regarded as ordinary S-waves trapped in the low-velocity surface layer. These waves are called Love-waves or shorter *L-waves* after the British mathematician A.E.H. Love (1863 - 1940) who first described this kind of wave. The speed of the L-waves, c_L, depends on the length (or frequency) of the wave. Such a wave is called *dispersive*. The speed is in-between the lowest and highest S-wave velocity of the different layers. Actually the situation is more complicated than so as there are two different wave velocities in a dispersive wave; the *phase velocity* and the *group velocity.*

The four types of waves, (P, S, R and L) and their particle movements are shown schematically in Figure 2.1.

The speeds of the waves are supposed to be correlated to the strength of the material. For concrete a correlation has been given by Bungey (1989).

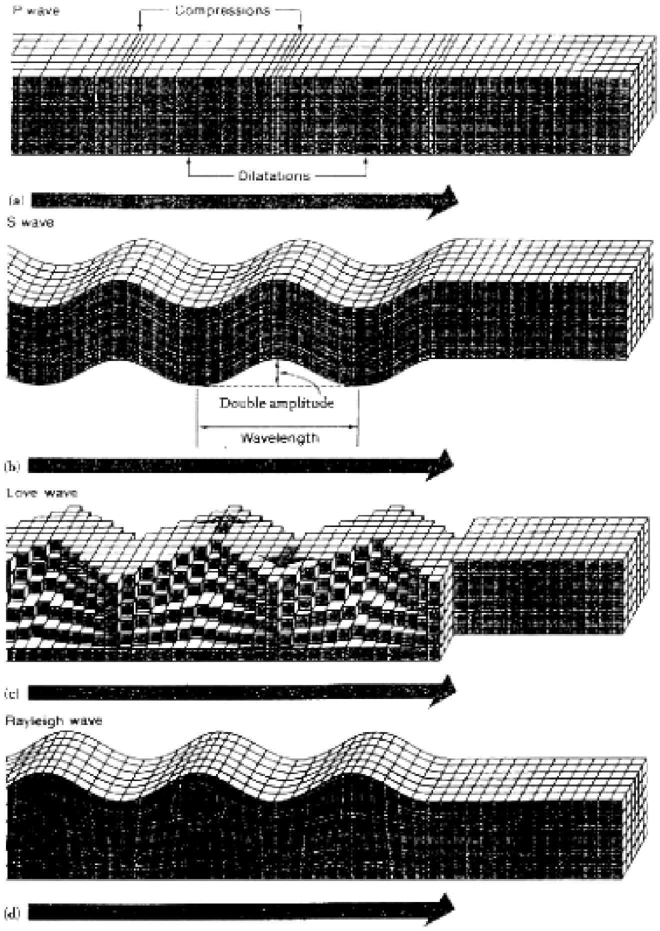

Figure 2.1. Schematic drawing of the particle movements in P-, S-, R- and L-waves (Bolt, 1976).

The waves described above exist in *homogenous* and *isotropic* materials. In a homogenous material the properties, as density and wave velocities, are the same in all locations of the material. Some materials contain inhomogeneities dispersed through the whole volume of the material. Such a material is called *turbid*.

Some material properties, as the wave velocities, might be different in different directions. Sandstone or shale was formed by sedimentation and therefore the material properties in the vertical direction may be different from the material properties in the horizontal directions. Such a material is called *anisotropic* or *ælotropic*. An anisotropic material may be homogenous.

The degree of inhomogeneity is not absolute; it depends on the wave length used in the investigations. If the wave length is many times longer than the characteristic dimension of the inhomogeneity the material interacts as a homogeneous material with the wave. If the wave length on the contrary is many times smaller than the characteristic dimension of the inhomogeneity the wave will be *scattered* in all directions into the material.

There are some important relations in wave mechanics, which should be mentioned here. First there is a relation between the wave length, λ, the frequency, f and the speed of the wave in consideration, c. This relation is

$$c = f \cdot \lambda \tag{2.1}$$

which states that the wave velocity is the product of the wavelength and the frequency. I.e. if a wave oscillates with a frequency of 1000 cycles/second and the wave length is 2 m, the wave propagates with a speed of 2000 m/s.

Another important matter is the *attenuation* of amplitudes of the wave with distance. There are two different kinds of attenuation; the first is the *internal dissipation* of energy also called internal damping the other is the *geometrical* attenuation. There are many internal processes in a geological material, which dissipate energy from the wave. One such process is dry friction between individual particles. The consequence is that the amplitudes of the wave diminish as the wave propagates. The diminution is often modelled by an exponential law i. e.

$$\hat{u}(r) = \text{const} \cdot e^{-\alpha \cdot r} \tag{2.2}$$

where r is the distance, e is a constant (= 2.718). α is the *dissipation constant,* which for dry friction and small values of α is

$$\alpha = \frac{\pi \cdot f}{Q \cdot c} \tag{2.3}$$

where π is a constant (= 3.142) and Q is a material constant, called the *goodness number* or simply the *Q-factor* , which is a measure of the dissipation by friction. There are different dissipation constants α_i for the different types of waves, i = P, S, R or L. Some α_P-values were given in Table 2.1.

The geometrical attenuation depends on the geometrical dimensions of the source and the structure of the medium. At distances close to the source in the *near field*, i.e. distances only a few wave lengths from the source, it is not possible to give a general formula for the attenuation. In the *far field* it is easier to give formulas if the shape of the source is given. For a point source i.e. a source of small dimensions the body waves (P and S) attenuate inversely proportional to the distance and the surface waves (R and L) attenuate inversely proportional to the square root of the distance. Mathematically this can be written

$$\hat{u}(r) = \text{const} \cdot r^{-n} \tag{2.4}$$

where n = 1 for P- and S-waves and n = 0.5 for R- and L-waves. The total attenuation from internal and geometrical dissipation gives the following formula

$$\hat{u}(r) = \text{const} \cdot r^{-n} \cdot e^{-\alpha \cdot r} \tag{2.5}$$

2.1.2 Seismic transmission method

This method uses the transmission of body waves (P or S) from one point, the *emitter*, to another point, the *receiver*, to test the material. The material may be homogenous or if it is inhomogeneous the result is the average values of the investigated physical entities.

There are basically two different ways to perform this test. One is by a *transient*; a relatively short pulse from the source, produced for example by a hammer blow. Another way is to use *steady-state* vibrations i. e. vibrations during a relatively long time, produced by a vibrator. Both methods can measure P- or S - waves by arranging the source and the transducers in the adequate positions. For both methods there must be two free and accessible surfaces opposite to each other in order to perform the tests.

The principle of the transient method is to measure the *travel time* between one observation point to another observation point on the object. A schematic drawing of a test is shown in figure 2.2.

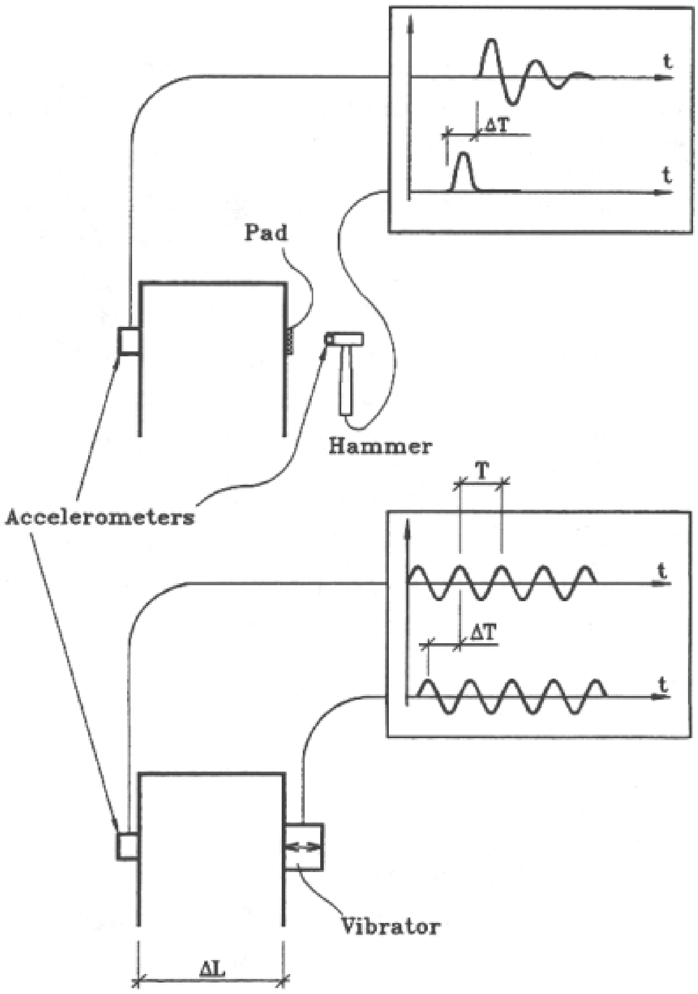

Figure 2.2. A schematic drawing of a seismic transmission test.

A hammer instrumented by an accelerometer excites the waves at one point and an accelerometer receives them at another point of the object. The signals from both transducers are recorded, either on paper or electronically, and the travel time, *DT*, between the recordings is measured. The travel time is the difference in time between the *first arrivals* of the recordings i.e. where the trace of the signal first departs from the zero line. The time difference between peaks of the signals may be subjected to other time delays and will not give an accurate result. By measuring the distance, *DL*, between the emitter and the receiver it is possible to calculate the average speed, c_i, of the wave under consideration (i = P or S) by

$$c_i = \frac{\Delta L}{\Delta T} \tag{2.6}$$

The principle of the steady-state method is to perform the measurements at different frequencies and to measure the *phase difference* between two signals. For two harmonically varying signals the phase difference is the time interval between two corresponding zero passages or corresponding peaks in terms of whole cycles; (points with the same phase). It is convenient to mathematically express one cycle as 2π *radians* instead of 360˚. From the phase difference, *Dä* it is possible to calculate the average speed, c_i, of the wave under consideration (i = P or S). The equation is

$$c_i = f \cdot \frac{\Delta L}{\Delta \theta} \qquad (2.7)$$

where f is the frequency in Hz of the vibration and *Dä* is the phase difference in cycles, i.e. *Dä* = 0.5 means 180˚ (or π radians) out of phase.

It should also be possible to measure the internal attenuation of the material. By knowing the geometrical attenuation the internal dissipation can be determined.

The quantities measured are in the case of the transient method; the length of the travel path, the time difference and the damping. In the case of the steady-state method the quantities measured are the length of the travel path, the phase differences at different frequencies and possibly the attenuation at different frequencies.

The equipment needed for this test method is an exciter, hammer with some protective pads or a vibrator. The delay of the waves in the pads must be known. Two accelerometers and a recorder to store the signals are also necessary. For the steady state method also a frequency analyser is needed. It is however possible to make the frequency analysis afterwards the field test in the office.

The limitation of the method is that only an average value of the wave speeds along the travel path will be obtained if not a tomographical analysis is applied.

The damages, which may be detected, are of the global type. The method is not common in NDT-geophysics but has been used for some particular projects as pillars in mines. In destructive testing, as measuring between bore holes, *cross - hole* tests is very common.

2.1.3 Seismic refraction method

This method uses the refraction of P-waves to test the material. The material has to be inhomogeneous with wave speeds increasing from the surface for the method to work. The result is a profile or a map of the interior of the material. The source is commonly a detonation or a big vibrator.

The principle is as following. For simplicity it is assumed that the stone under consideration consists of only two different materials; a homogenous material with depth H overlying a homogenous material, with greater P-wave velocity, of infinite depth, see figure 2.3.

When a P- or S-wave travels in a homogenous medium its path is a straight line. When it encounters a different medium the path changes its direction. The wave is *refracted*. Another part of the wave is *reflected* back into the medium. The relations between the incident, θ_i, the reflected, θ_{refl} and the refracted, θ_{refr} angles are the well-known formulas by Snell

$$\theta_{refl} = \theta_i \qquad \text{and} \qquad \frac{\sin(\theta_{refr})}{c_{P,2}} = \frac{\sin(\theta_i)}{c_{P,1}} \qquad (2.8)$$

where $c_{P,1}$ and $c_{P,2}$ are the P-wave speeds of medium 1 and 2. One consequence of this is that for a particular angle of incidence the refracted ray will travel parallel to the surface of discontinuity, $\ddot{a}_{ref} = 90^o$ if the P-wave speed of material 2 is greater than the P-wave speed of medium 1. This wave will act as source for waves in medium 1. But as this source travels faster than the speed of the P-waves in medium 1, the wave front in medium 1 will be a straight line. This wave, which travels from the surface of discontinuity out towards the free surface and eventually will appear at the surface is called, *head wave*. Once the head wave has appeared at the surface it will travel with the speed of the P-wave in medium 2. It is thus possible to measure the speed of the P-wave in medium 2 by measure the first arrival of signals recorded at the surface of the material as is schematically shown in figure 2.3. The first arrival times are plotted in a time distance diagram called *travel-time diagram*. The curve obtained in the diagram will for this special case contain one *break point* denoted X^* in figure 2.3. The second part of the curve if it is extrapolated will give an *intercept* with the time axis, t_0. By measuring either of these entities it is possible to calculate the depth of the superficial layer. The P-wave speeds, $c_{P,1}$ and $c_{p,2}$, of the layers are the inverted values of the slopes of the curves in the travel time diagram. If the material consists of several layers overlying the infinite medium there will be as many break point as there are layers.

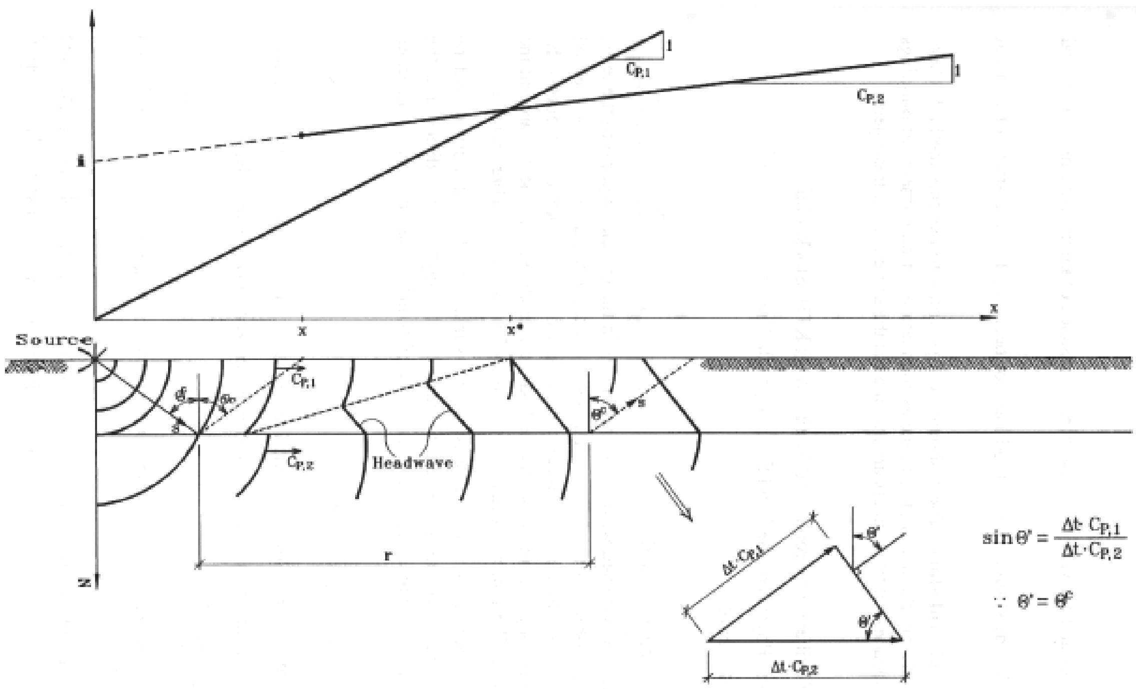

Figure 2.3: The principle of seismic refraction.

It is also possible to use S-waves for the test but it is more difficult since the signals then might be obscured by the P-waves.

The quantities measured are the travel times and the locations (distances).

The equipment needed for the tests is transducers (seismometers or accelerometers) and a multi-channel data acquisition system.

The limitation of the method is that the P-wave velocity has to increase monotonically with the distance from the surface.

Only global damages will be detected by this method.

The literature of this method is huge. Besides the works quoted above worth mentioning is Sjögren (1984). The method is established since decades and has been used extensively all over the world for investigating the ground for smaller distances in civil engineering works and for very long distances, thousands of kilometres, in geophysical research works.

2.1.4 Seismic reflection method

This method uses the reflected waves from *reflectors* in the ground to perform the tests. The reflectors may be surfaces of discontinuities or concentrated defects. In the method of refraction the transducers were located in a line from the source and outwards, sometimes to very long distances. In this method the transducers are located around the point of excitation. The source is often a detonation of explosives or a big vibrator.

When a mechanical wave hits a surface of discontinuity it will be reflected. How much will be reflected depends on the angle of incidence and the *specific impedance*, z, which has the dimension of N/m^3. It can be written in three different ways i.e.

$$z = \sqrt{G\rho} = \rho \cdot c_S = \frac{G}{c_S} \tag{2.9}$$

where ρ is the (total) *density* of the material and *G* is the *shear modulus* of the material.

For vertically propagating and reflected waves the *reflection coefficient, R*, is

$$R = \frac{z_2 - z_1}{z_2 + z_1} \tag{2.10}$$

The reflection coefficient is defined as the ratio between the amplitudes of the reflected and the incoming waves. A travel time diagram of reflected waves is shown in figure 2.4.

The curves are hyperbolas whose equations are for the case with one layer with thickness, *H*, on top of an infinite layer:

$$T = \frac{\sqrt{(2nH)^2 + x^2}}{c_i} \tag{2.11}$$

where n is the number of reflections in the surface of discontinuity. c_i is the speed of the investigated wave (i = P or S). A difficulty is that P-waves will give reflected P- and S-waves and vice versa. The equation (2.11) is valid for those rays, which are only P-waves or S-waves. After only a few reflections the picture of P and S waves is very complex. When there are several layers there will also be multiple reflections inside the medium. The signal processing of the recorded signals from seismic reflection tests is therefore important and it has reached a sophisticated level particularly in the petroleum prospecting industry. For an excellent treatment of this kind of signal processing see Claerbout (1976).

The entities measured are travel times and locations.

The equipment needed for the tests are transducers, seismometers or accelerometers, and a multi-channel data acquisition system possibly containing some filter functions.

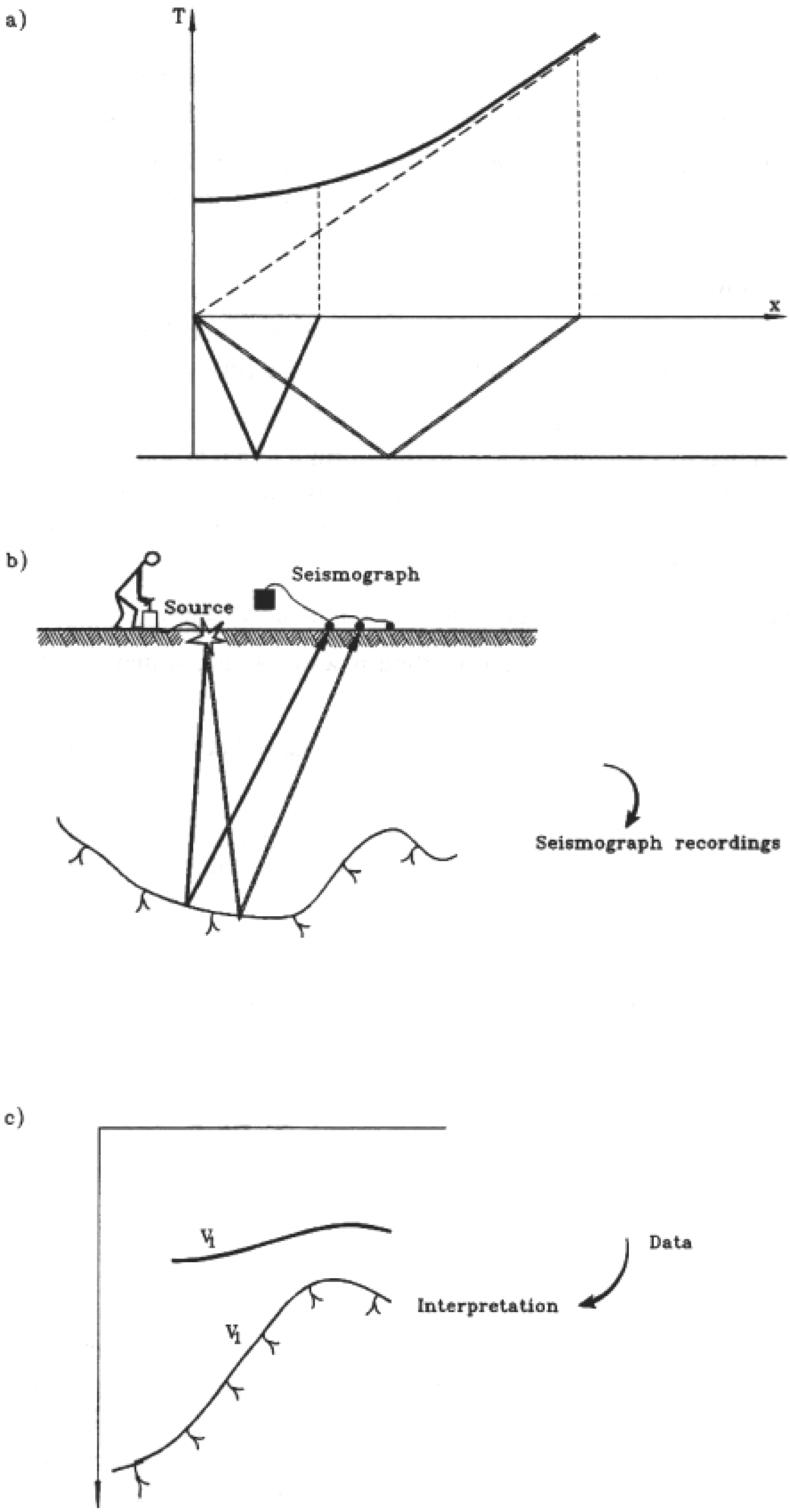

Figure 2.4. The method of seismic reflection and its travel time diagram (Triumf, 1992)

A limitation of the method is that the vertical axis in the travel time diagram is a time axis. In order to transform that to a length axis, i. e. to transform it to a real sounding of the ground, the P-wave speeds of the different layers must be known. In most geophysical situations and for the geological interpretation of the result it is sufficient to work with the travel time diagram.

The seismic reflection method can be used both for local and global damages. The seismic reflection method is an established method in geophysics, particularly in the petroleum industry.

2.1.5 Seismic surface wave method

This method applies the mechanical surface waves, R-waves, to investigate the medium. Surface waves penetrate the medium from the surface down to a depth of approximately one wave length. This means that by using different wave lengths it will be possible to investigate the medium to different depths. Since the wave lengths of the R-waves are inversely proportional to the frequency c.f. eq. (2.1), lower frequencies penetrate to greater depths than higher frequencies.

There is a very approximate method, which has been used since the 50’s, but during the last decade a more accurate method has appeared. The relatively new method is called the SASW-method (Spectral Analysis of Surface Waves) and is founded on the Thomson-Haskell method, which has successfully been used in seismology since the 60's. For engineering purposes it was developed primarily by S. Nazarian and K. Stokoe, (Nazarian, 1984). It has been mostly applied in road engineering to investigate the pavements but also for the evaluation of concrete dams and the effectiveness of soil improvement techniques. The theory of the method is described in Aki - Richards (1980) and Woods (1994). Svanberg (1995) gave a shorter description but with the full mathematical treatment included together with some practical examples. A great advantage with the seismic surface wave method is that the wave speeds of the individual layers can vary arbitrarily.

In order to produce different wave lengths a vibrator driven with different frequencies or a short mechanical pulse should be used. If a transient pulse excites the ground it will be necessary to perform a frequency analysis before applying the Thomson-Haskell method. The method only requires two transducers; seismometers or accelerometers. These receivers are normally oriented to detect only the vertical component of the R-wave. This means that the method is relatively easy to apply in the field. The test requires little equipment and takes only a short time to perform. The source can be a drop weight, a hammer blow on a metal plate or a vibrator. The method is illustrated in figure 2.5.

If the medium is homogenous a harmonic varying R-wave propagates with a speed, which is independent of its frequency. If the medium is non-homogenous the speed of the R-wave, c_R, will depend on the frequency; the wave is *dispersive*. A plot, *dispersion diagram,* of the speed as a function of the frequency will act as a 'finger print' of the non-homogenous medium, see figure 2.5. For a given profile it is possible to calculate such a plot by the Thomson-Haskell procedure. For the details the reader is advised to the above-mentioned literature.

The measurements are performed by the steady-state technique described in section 2.1.2. The R-wave speed is calculated by using eq. (2.7) above.

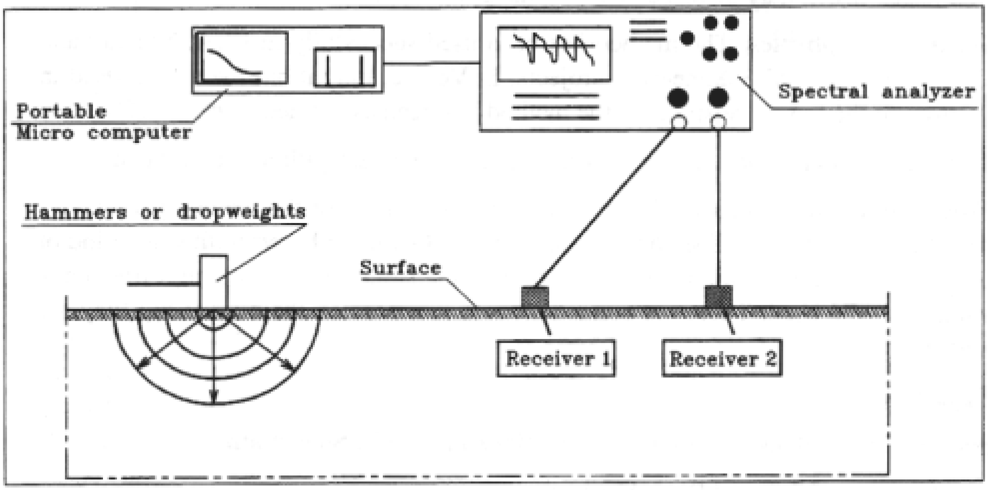

Figure 2.5. Field arrangement of the seismic surface wave method (Sheu et. al, 1988).

The SASW method consists of three stages: 1) Collection of experimental data, 2) Determination of the dispersion curve from the experiments and 3) Inversion of the dispersion curve to obtain the soil profile. The last step is taken by first assuming a profile and then calculating its dispersion curve and thereafter comparing the calculated curve with that from the experimental data. If there are differences the assumed profile is modified and a new dispersion curve is calculated. The calculated dispersion curve is compared to the experimentally obtained one and so on. Today there is no direct way to invert the experimental data to the soil profile.

The quantities measured are distances and phase differences.

The equipment needed for the tests are transducers, seismometers or accelerometers, together with a two-channel data acquisition system containing frequency analysing functions and filters.

One limitation of the SASW method, in its state today, is that the trial and error procedure when analysing the results may take time. But according to the expertise an experienced analyser need little time to analyse the recordings.

The damages, which may be detected, are of the global type. The method has been used successfully in USA, Norway and the Netherlands in civil engineering projects. In Venice, Italy it has even been used in the bottom of the sea. In seismology the method has been established since the 60's.

2.1.6 Impact echo method

The impact echo method, IE-method, has been developed to test concrete structures. It uses reflections of mechanical waves from reflectors inside the structure (Carino et al, 1986 , Carino and Sansalone, 1988) and is thus a kind of seismic reflection method.

A stress pulse is introduced in the material from a blow of a hammer, the *impactor*. The stress pulse consists of both P-waves and S-waves and when they meet a discontinuity they will be reflected back to the surface. The surface will reflect the pulse back into the material where it will again meet the discontinuity and so on. In this way their will be a repetitive movement at the surface which can be measured by a transducer. The movement can be regarded as a resonance between the free surface and the discontinuity. The frequency of the motion is measured. The method is similar to the seismic reflection method described in section 2.2 but there the travel times were detected.

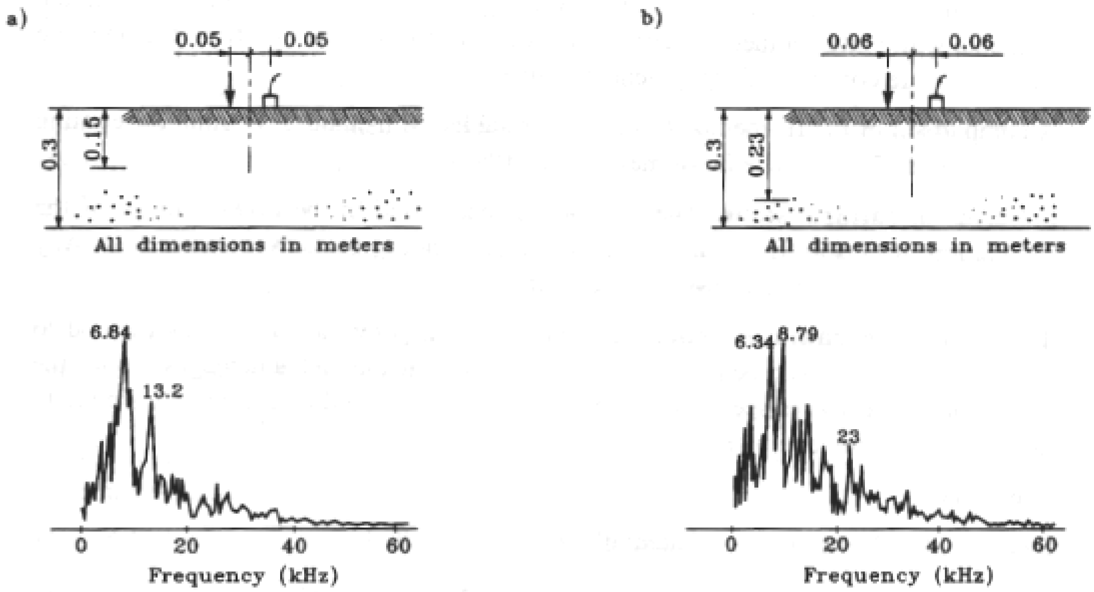

Figure 2.6. The impact echo method (Sansalone and Carino, 1988).

The impactor consists often of a sphere of steel, which is driven by a spring. Several spheres with different diameters can be used. The choice of the diameter makes it possible to use different frequencies as the diameter is inversely proportional to the dominant frequency of the pulse. The results must be calibrated against a known distance.

For a surface layer with thickness, *H*, and shear wave velocity, c_S, on top of an infinite medium, see figure 2.6, the frequency, f_0, detected by the impulse echo method will be either

$$f_0 = \frac{c_S}{4H} \qquad \text{if } z_{layer} < z_{infinite\ medium} \qquad (2.12)$$

or

$$f_0 = \frac{c_S}{2H} \qquad \text{if } z_{layer} > z_{infinite\ medium} \qquad (2.13)$$

The quantities measured are the length of a travel path (for the calibration), the spectral amplitudes at different frequencies.

The equipment needed is accelerometers and a one-channel frequency analyser. There is equipment commercially available for this kind of test.

Some limitations of the method are; a calibration is needed in order to determine the location of the damage and that the equipment available today is rather bulky.

Both global and local damages should be able to detect with this method. This is a recently developed method. It can not be regarded as established. However the Swedish State Power Board (Vattenfall AB) is currently investigating the method. According to Wiberg (1994) it can be used to investigate elements with plate geometry where there will be a strong reflection from the opposite side. There are commercial equipment available.

A comparison of the IE-method to the more established method of Ground Penetrating Radar (see ch. 3.1) is made in Momayez et al (1994).

2.2 ULTRASONIC METHODS

Ultrasonic methods are well established in flaw and crack detection in the mechanical industry. They are also applied in control of concrete (Wiberg, 1994) and have been used in the investigation of cultural stone. It is probably appropriate to say that ultrasonic methods are the most used NDT-method to cultural stone. Several ultrasonic methods exist. Wiberg (1994) made a comprehensive review of these. The following is mainly taken from her review.

Actually all above mentioned methods and the acoustic emission methods described later could be used with ultrasonic waves but as ultrasonic methods have become a technique by itself they are described here separately.

Both the exciter and the receivers are normally piezoelectric devices in ultrasonic tests. Ultrasonic frequencies are those which are above audible sound i. e. above 20 kHz.

The method of Ultrasonic Pulse Velocity, (UPV), is very similar to the seismic transmission method described in Ch. 2.1.1 but with the application of ultrasonic frequencies.

The method of Ultrasonic Pulse Echo (UPE) is very similar to the seismic reflection method described in Ch. 2.1.3 but again applying ultrasonic frequencies.

The method of Seismic Echo (SE) is also a reflection method but the frequencies used are lower and produced by a hammer. In addition to obtaining travel times it also gives the force time history of the impact.

The method of Impulse Response (IR) is a modification of the Impact echo, IE, method described in Ch. 2.1.6. This method measures also the force time history of the impact. It obtains a so-called impulse response spectrum, which is a transfer function between the measured entity, often an acceleration, and the force. From the impulse response spectrum it is possible to calculate the dynamic stiffness and the distance to a reflector.

The method of Quantitative Ultrasonics (QU) may be used both in transmission and in reflection. It takes into consideration wave propagation in turbid media. This method is used to investigate distributed damages as micro-cracks and porosity variations. The signals are statistically treated and the result is a measure of the quality of the material (Wiberg, 1993). The method has not yet been tested in the field.

The method of Acousto Ultrasonics (AU) was developed for elements of composite materials. The entire element is modelled by what is called stress-wave-factors. By this method it is possible to monitor changes of the element with time.

The quantities measured for the different methods of ultrasonics are the corresponding quantities measured in the seismic methods.

The equipment needed for ultrasonic measurements is special designed equipment, which is highly sophisticated and expensive. In principle it contains of ordinary transducers and a data acquisition system.

One of the limitations is the bulkiness of the equipment.

Both global and local damages can be detected with this method. The methods of ultrasonics are well established and used for many different purposes in mechanical and civil engineering.

2.3 HAMMER METHODS

The methods described above use hammers to excite the mechanical waves but after the waves are created the measurements are made on the propagating waves. There is a possibility to perform the measurements on the hammer itself as the behaviour of the hammer reflects the conditions of the stone material in the vicinity of the impact point. Two methods are described here; the first one, the *Schmidt hammer*, is today hardly a non-destructive method and the second one, the *hammer impact*, is based on a phenomenon which has been noticed during the work at the Division of soil and rock mechanics at the Royal Institute of Technology (KTH). It should be possible to adjust both of these methods so they can be used to non-destructively test cultural stone.

2.3.1 Rebound methods, Schmidt hammer

The Schmidt hammer method (Schmidt, 1951) is today routinely used to test the strength and the quality of rock and hardened concrete. For the latter there are standardised methods for obtaining the compressive strength of hardened concrete in Swedish Standard SS 13 72 37, SS 13 72 50 and SS 13 72 52. The second one uses only the rebound number (see below) and the third one uses both the rebound number and the P-wave velocity of the hardened concrete to determine the strength of the concrete.

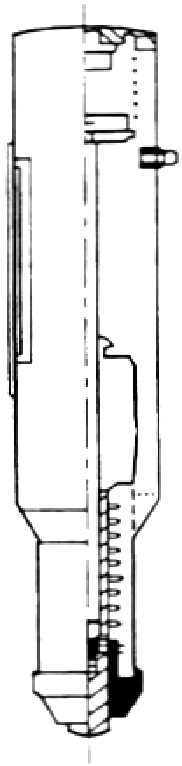

Figure 2.7. The Schmidt rebound hammer (from Kolaiti, 1993)

The device consists of a spring loaded steel mass that is automatically released against a plunger when the hammer is pressed against a concrete or a rock surface. A small sliding pointer indicates the rebound of the hammer on a graduated scale (see Figure 2.7).

The principle of the test is based on the absorption of part of the stored elastic energy of the spring through plastic deformation of the rock surface and mechanical waves propagating through the stone while the remaining elastic energy causes the actual rebound of the hammer. The distance travelled by the mass, expressed as a percentage of the initial extension of the spring, is called the *Rebound number*, (Kolaiti et al, 1993). There are two types of hammers: L-type for rocks and N-type for concrete.

The quantity measured is the rebound number (the height of the rebounded hammer). The equipment needed is a commercially available Schmidt hammer.

As used today the method has some limitations; a) very fractured and closely jointed rocks are difficult to test. b) The method is not applicable to extremely weak rocks. c) Non-homogenous rocks are difficult to test.

The damages detected by the method must be confined to the surface of the stone. The Schmidt hammer method is well established in civil engineering for testing concrete and rock with the above mentioned limitations.

2.3.2 Hammer impact

This method has only been suggested and no systematic investigations has so far been carried out. Some experiments will however be performed during summer 1995 at Royal Institute of Technology, Stockholm.

The idea of the method is to measure the force time history during the impact. It has been noted during experiments that an impact on an intact stone creates a distinct force time pulse while an impact on a weak or soft stone creates a longer and more blunt force time pulse, see Figure 2.8. This phenomenon should reflect the conditions of the stone. The impact process is discussed in Roesset et. al. (1994). It is the superficial parts of the stone, which mostly influence the response of the hammer. Hence this method should have special importance in the study of cultural stone as these parts are most damaged.

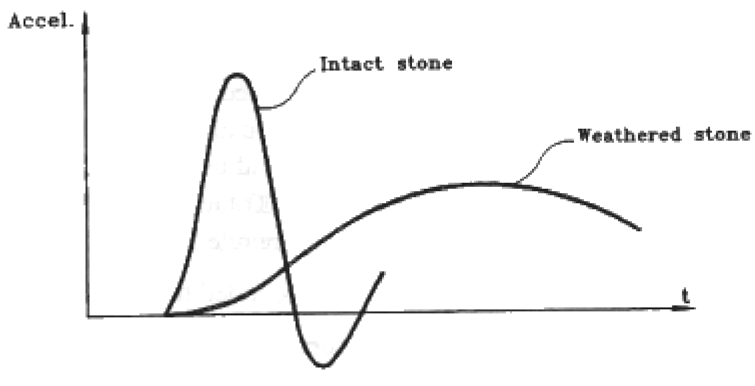

Figure 2.8. The shape of the signals from the force time history.

The quantities measured are force and time. The equipment needed is a force transducer (accelerometer) and a memory oscilloscope where the data can be stored.

Limitations to the method is that only the surface layer may be investigated and that the hammer blow must be gentle not to damage the stone at the point of impact.

Only local damages in the surface layer may be detected by the method. A similar method is used in civil engineering when testing road pavements.

2.4 ACOUSTIC EMISSION METHODS

When a brittle material is stressed or strained elastic waves are generated. These waves are called *acoustic emission* (AE), or *microseismic activity*, (MA). The source of the AE/MA stress waves in rock can be microcracking, dislocation movements or other phenomena. The rate of occurrence of AE signals is an indication of the internal damage (Li and Shah, 1994).

The stress waves, P and S-waves, propagate to the surface where they can be recorded and analysed. This is the same situation when earthquake sources deep in the ground produce stress waves, which are recorded by seismological observatories. The signals are mostly measured by piezoelectric transducers. A schematic drawing of the method is presented in figure 2.7. By using three or more transducers it is possible to localise the source. Mostly the numbers of events per unit time are recorded or the number of *counts* per unit time. Each event is formed by a number of counts, which are the peaks above the background noise threshold of the recorded event.

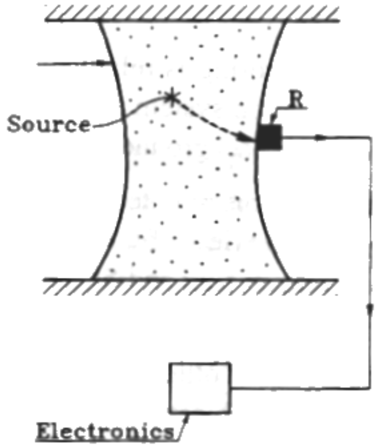

Figure 2.9. Acoustic emission (Hardy, 1981)

Other parameters of the signal e.g. the frequency content, the energy, the duration of each signal are sometimes also obtained and analysed.

There are many kind of stress situations a stone in a masonry can be subjected to (Montoto et al, 1991a):

a) uniaxial compressive stresses in pillars supporting a building,

b) tensile stresses related to floor subsidence,

c) bending stresses in the lintels above windows and doors,

d) thermal stresses on the sunny walls of a building,

e) stresses due to water volume increase due to freezing,

f) swelling stresses when smectitic clays are present,

g) stresses developed in voids of the rock due to crystallisation or hydration of soluble salts, etc.

The different methods of AE/MA offer a possibility to investigate all these different stress situations.

The method may also be used in the evaluation of the effectiveness of conservation treatments, specifically the use of consolidants and protectors.

The AE technique can be very sensitive. In one case micro fracturing during capillary uptake of water by samples of sandstones was recorded.

The quantities measured are of different kinds. They may be arrival times and acceleration time histories from which it is possible to deduce the number of counts, duration and frequency content of the signal.

The equipment needed is accelerometers and a data acquisition system, which is commercially available.

One limitation of the method is that to perform a test is rather complicated procedure with relatively complicate instruments.

The basic equipment for AE/MA monitoring is relatively simple; a transducer which often is an accelerometer, an amplification system and a recording equipment. A filter system is also included to take away the background noise.

Acoustic emission techniques have been used in civil engineering for many years, for a good review of the applications see Hardy, (1982). It is also much used in testing of concrete, c. f. Li and Shah (1994).

3. ELECTRICAL METHODS

There are more electrical geophysical test methods than there are mechanical. Some use the naturally occurring electrical fields and others require artificially introduced electrical currents. Electrical methods are mostly used to search for metals and minerals at relatively shallow depths, down to 500 m. In cultural stone natural electric currents probably do not exist so the electrical field has to be artificially introduced in testing stone with electrical methods.

Three methods, which already have been applied or should have a potential to be applied in the study of cultural stone have been selected. These are the radar, resistivity and electromagnetic methods.

3.1 RADAR METHODS

The radar methods for testing rock started early in this century and has developed together with the improvements of other radar methods. Recently a breakthrough in the application of radar methods have occurred in civil engineering called Ground Penetrating Radar (GPR). In Sweden it was introduced to civil engineering by Ulriksen (1982). A good introduction, in addition to Triumf (1992), to radar methods is a booklet from the Finnish Geotechnical Society (1992). There have also been five international conferences on ground penetrating radar, the last one in Kitchener, Ontario, Canada, 1994.

The basic principle of ground penetrating radar is that an antenna transmits a short electromagnetic pulse with frequencies in the FM-radio band, normally 80 MHz to 1GHz. When the pulse reaches an electric interface in the medium some of the energy is reflected back and the rest is transmitted, see Figure 3.1.

The radar system measures the time elapsed between the excitation of the wave and its reflection, much in the same way as in the seismic reflection method described in chapter 2.1.3. The velocity of the electromagnetic wave in a medium, c_m, is

$$c_m = \frac{c}{\sqrt{\varepsilon_r}} \quad (3.1)$$

where c is the velocity of electromagnetic waves in vacuum, 300 000 km/s or 0.3 m/ns. The *constant of relative dielectricity*, ε_r, depends of the material and the frequency used. Some values of ε_r are 1 for air, 81 for water and around 5-10 for rock.

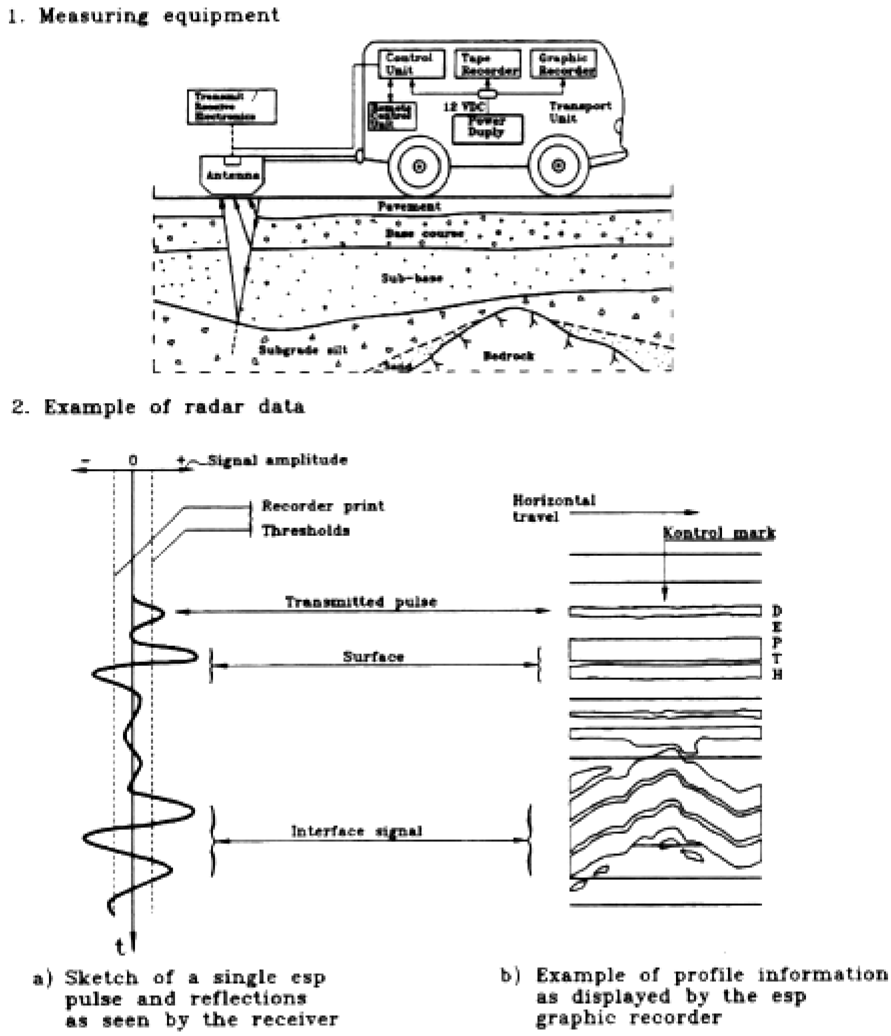

Figure 3.1. Principle of the ground penetrating radar (Finnish Geotechnical Society, 1992)

The reflection coefficient, *R*, for a wave in material 1 reflected by material 2 can be written

$$R = \frac{\sqrt{\varepsilon_{r,2}} - \sqrt{\varepsilon_{r,1}}}{\sqrt{\varepsilon_{r,2}} + \sqrt{\varepsilon_{r,1}}} \quad (3.2)$$

where $\varepsilon_{r,i}$ is the constant of dielectricity in medium i. If this constant changes from one material to another there will be a reflection. The square root of the dielectricity constant plays the same role as the mechanical specific impedance, *z*, c.f. eq. (2.10).

Electrical waves are also attenuated during their propagation through a medium. As in mechanics there is a geometrical attenuation and an internal attenuation. The geometrical attenuation follows the same rules as in mechanics i.e. r^{-n} where n = 1 for spherical propagation and $r^{-0.5}$ for cylindrical propagation. The internal attenuation follows the exponential law $e^{-\alpha . r}$ where the attenuation constant, α, is in 1/m or Neper/m:

$$\alpha = \frac{1635 \cdot \sigma}{\sqrt{\varepsilon_r}} \tag{3.3}$$

where σ is the *conductivity* of the medium. For a definition of conductivity see the comments on eq. (3.4) below. Some values of σ are; 0 for air, 0.003-0.0001 S/m for water and 0.01- 0.00001 S/m for rock (S is *Siemens*).

In the GPR-technique the measurements are repeated at short intervals while the antenna is in motion. The output signals, *scans*, are drawn consecutively by means of an intensity recorder, which produces a continuous profile of the electric interfaces in the material. Usually the antenna is directed vertically downwards but there is also a possibility to direct it at an angle to the vertical axis, *side scanning* radar.

The equipment consists of an antenna a data acquisition system.

The limitation of the method is that it can only be applied to non-conducting materials. In civil engineering the penetration ability is reduced in conducting materials as clays. In this context water is regarded as a good conductor of electrical currents. The results from an investigation must be calibrated against known depths, as it is the travel time, which is measured. Today the equipment is expensive.

Both global and local damages are possible to detect with this method. The method is well established in geophysics and civil engineering. It is used in determination of the depth to rock and ground water, localisation of sand and gravel deposits, localisation of blocks, investigations of roads and archaeological investigations.

3.2 RESISTIVITY METHODS

The methods of electrical resistivity are used to measure the *apparent resistivity* of the ground. The variations of the apparent resistivity are due to the variations in the composition of the ground.

The electrical resistivity of a material is defined as the resistance of a cylinder with a cross section of unit area and with unit length. If the resistance of a conducting cylinder having a length, L, and cross section area, A, is R, then the resistivity, ρ, is expressed by the formula

$$\rho = \frac{R \cdot A}{L} \tag{3.4}$$

The unit of resistivity is ohm-meter, Ωm. The conductivity, σ, of a material is defined as the reciprocal of resistivity, i.e. $\sigma = 1 / \rho$.

The porosity and chemical content of the water filling the pore spaces are more important in governing the resistivity than the conductivity of the mineral grains of which the rock is composed. The salinity of the pore water is probably the most critical factor determining the resistivity, (Dobrin, 1976). The range of resistivities among rock materials is enormous extending from 10^{-5} to 10^{15} Ω-m. Table 2 shows some resistivities for water-bearing rocks, (Keller, 1966).

Table 2. Resistivities (Ω-m) for water-bearing rocks

Geologic age	Marine sand, shale, graywacke	Terrestrial sands, claystones, arkose	Volcanic rocks (basalt, rhyolite, tuffs)	Granite, gabbro etc.	Limestone, dolomite, anhydrite, salt
Quaternary, Tertiary	1 - 10	15 - 50	10 - 200	500 - 2 000	50 - 5 000
Mesozoic	5 - 20	25 - 100	20 - 500	500 - 2 000	100 - 10 000
Carboni-ferous	10 - 40	50 - 300	50 - 1 000	1 000- 5 000	200 - 100 000
Pre-Carboni-ferous Paleozoic	40 - 200	100 - 500	100 - 2 000	1 000- 5 000	10 000 - 100 000
Precambrian	100 - 2 000	300 - 5 000	200 - 5 000	5 000 - 20 000	10 000 - 100 000

Normally an increase of the resistivity of natural stone is expected with time because the compaction increases with time. This is more or less also the rule.

The method as it is normally used in geophysics is based on the introduction of a direct current, I, through electrodes at the surface of the material. The electrical potential, U associated with this current is measured between two other electrodes on the same surface, see Figure 3.2.

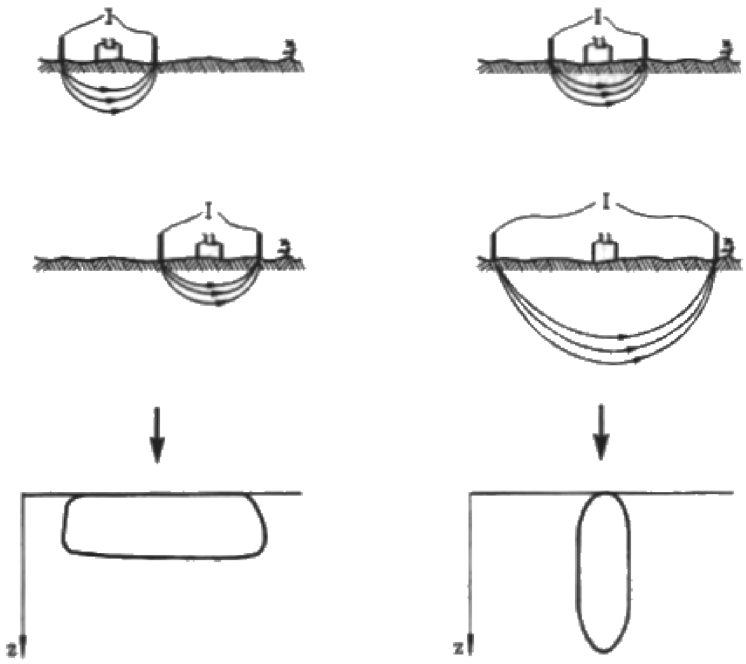

Figure 3.2. Arrangement of a resistivity test (Triumf, 1992)

The potential, U, is measured and the apparent resistivity is calculated according to:

$$\rho_a = \frac{2\pi \cdot U}{I} \cdot \frac{1}{\frac{1}{r_1} - \frac{1}{r_2} - \frac{1}{r_3} + \frac{1}{r_4}} \qquad (3.5)$$

Eq (3.5) can be regarded as the definition of apparent resistivity. If the electrodes are laid out in a line and their distances are increased in a systematic manner it is possible to determine the variation of the resistivity with depth. There are many electrode configurations which can be used some of them are Wenner, Schlumberger and the dipole method, (Dobrin, 1976).

The quantities measured are the differences in electrical potentials and locations.

The equipment needed is non-polarizable electrodes and a two channel data acquisition system. At the Technical University in Lund an automatic multi-channel system has recently been developed.

One limitation of the method is that different soil profiles can give the same experimental results, i.e. the same potential U. Thus some kind of calibration with another method must be performed. In the Nordic countries it is difficult to make tests during winter as it is not possible to place the electrodes in the frozen ground.

Only global damages can be detected by this method. The method is well established in geophysics particularly for detecting the depth to the ground water surface, depth to the rock surface, quality of water, spreading plumes of contaminants and many other applications.

3.3 ELECTROMAGNETIC METHODS

The electromagnetic method as used in geophysics is mostly applied to mineral prospecting. For that purpose it is the most widely used method.

The method is based on the induction of electrical currents in buried conductors by electromagnetic waves generated at the surface of the ground. The waves are generated by alternating currents, which are passed through loops of wire. The frequencies are in the range of a few hertz to a few megahertz. When the waves pass through a conducting body they induce currents in the body. These currents become a source for new electromagnetic waves, which can be detected by another coil, (Dobrin, 1976).

There are several types of electromagnetic methods (Triumf, 1992). Two of them are the *VLF method* and the *Slingram method*. In the VLF (very low frequency) method the sources are distant stationary emitters which are situated at several places around the world. The frequencies are in the range of 15 - 25 kHz.

In the slingram method the emitter and the receiver coils are carried together. They can also be aboard an airplane. Commonly the axis of the coils is vertical and their distances are in the range of 20 - 100 meters. The frequencies emitted are often in the range of 800 - 18 000 Hz. It is also possible to arrange the emitter coil and the receiver coil on a single pole.

The quantities measured are the electric potentials.

The equipment needed for the test was described above.

A limitation of the method is that it is difficult to make quantitative interpretations. Many electrical configurations in the ground may yield the same experimental results. They are also susceptible to electrical nets and railway traffic.

Only locally occurring metal objects will be found with this method. The method is a well-established method in geophysics where it is primarily used to study clay deposits, salinity of water, depth of weathering in rock, weak zones in the rock basement etc.

4. CONCLUSIONS

The following table is a summary of the different methods.

Table 4.1. Summary of the different methods.

Physical Areas	Methods	Status of the method in geophysics	Status of the method in cultural stone	Estimated technical feasibility in cultural stone	Estimated economic feasibility in cultural stone	Type of damage
Mechanical	Transmission	+++	+	+++	+++	G
	Refraction	+++	0	+	+	G
	Reflection	+++	0	++	+	G and L
	SASW	++	0	+	+	G
	IE	+	+	++	+++	G and L
	US	+++	+++	+++	+++	G and L
	Schmidth.	+++	0	+	+	L
	Hammer	+	0	++	+++	L
	AE/MA	+++	++	++	++	L
Electrical	Radar	+++	++	++	+	G and L
	Resistivity	+++	0	++	++	G
	EM	+++	0	+	++	L

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List of Figures

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Figure 3.2. Arrangement of a resistivity test