Arch Bridges
ARCH'04
P.Roca and E. Oñate (Eds)

NEW DEVELOPMENTS OF SONIC TESTS APPLIED TO THICK MASONRY STRUCTURES

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Key words: Retaining Masonry Wall, Spectral Analysis of Surface Waves

Abstract. *Among the different typologies characterizing historic masonry structures, those witch present the most unknown physical and mechanical properties of their internal components, are the structures shaped by massive masonry. The reference is made to examples like the lower part of bell towers, high ditch walls of citadels, retaining walls of rivers or canals, as well as spandrels and piers of arch bridges. How to know the effective structural and load bearing hidden thickness as well as the internal grade of integrity of the wall or pier is still at present a debating issue.*
Among the wide variety of sonic methods used for detection of internal discontinuities, the Spectral Analysis of Surface Waves (SASW) was developed since decades ago, with different applications, mainly in geothecnical area and reinforced concrete structures, both in the time domain and the frequency domain. In the case of massive masonry elements, techniques analyzing and processing the data with models using phase velocity, frequency-wave number and power spectral analysis seem to present high reliability of detecting the material discontinuities, even of small dimension.
Recalling the actual background of sonic non-destructive test different applications, the paper describes the calibration procedure used and the techniques implemented, in term of technological in-situ application and data processing, for the investigation of a retaining masonry wall of an historic water canal near the masonry abutments of a bridge, interested by heavy traffic downtown Milan.

1 INTRODUCTION

Massive masonry structural elements, like fortification walls, bridge abutments, river or canal side walls, may be made with a number of material stratification and geometric thickness, like the example shown in figure 1-a,b. The assessment of the static capacity of the structure requires a deep investigation, in particular regarding either material characteristics, geometrical actual dimensions of each structural components and different grade of inside compactness.

Localized core drill tests may give direct proofs of the hidden above characteristics, but they cannot provide a field picture.

Design engineers and researchers are working together since a number of years with the aim of setting up efficient and reliable nondestructive techniques able to render a complete reliefe of the hidden unknown properties of the masonry structures.

Among a wide variety of different nondestructive tests, the sonic methods are those today widely implemented for in-situ investigation.

The paper describes a short review of the today capabilities, from the point of view of structural assessment, of different sonic methods; then it describes an advanced methodology of SASW sonic test applied to existing masonry structure, characterized by an important thickness. The method, originally developed in the geophysical applications, is today widely applied, for example, for the detection of underground voids. In the case of masonry structure, voids and discontinuities, as well as not visible changes in the geometrical thickness, are not so evident as are in the ground. As a matter of fact, in the case of underground investigation we may refer to the presence of macro-voids, while in the case of structural masonry elements we have to investigate about the presence of micro-voids, i.e. lack of material in the mortar layers or penetration of even small cracks.

Figure 1-a,b: Typical material stratification of ancient masonry structure

2 NONDESTRUCTIVE MEASUREMENT OF MASONRY STRUCTURAL ELEMENTS

The evaluation of the reliability of existing structures is a key element in any maintenance or rehabilitation plan. This evaluation should be based on realistic measurements of different variables such as geometry and material strength. In many cases, geometrical variables such as masonry wall thickness cannot be measured directly because of accessibility problems. Thus, they may be measured with destructive tests. However, these tests are expensive and sometimes impossible to perform at regular spacings. Conversely, nondestructive tests (NDT) are fast and economical, and can be used in-situ without major disruption to the normal operation of the structure. Acoustic or ultrasonic pulses emitted by a transducer propagate through the structure and are detected by a second transducer. If the wave velocity of the medium is known, the thickness of the structure can be computed from different configurations of the transducers. Wave velocity depends on the stiffness and mass of the medium, thus variations of these properties should be considered for the evaluation of geometrical parameters. The measured signals from the transducers (velocity, acceleration, or pressure) are recorded and analyzed in the time domain. However, complementary information can be obtained from the frequency domain or Fourier analysis of the signals; which provides information of frequency content, wavelength, and attenuation characteristics of the signals. Wavelength information is crucial for the analysis of nondestructive tests; because, the ratio of the wavelength to the size of the medium discontinuities governs the wave-material interaction (e.g. reflection, spreading, scattering).

However some laboratory research works on masonry wallettes[i] suggested intrinsic difficulties of ultrasonic method to catch physical properties of damaged masonry samples. It was underlined that the intrinsic high attenuation characteristics of ultrasonic waves, make ultrasonic method not suitable for masonry thick structures. As a matter of fact, different application of sonic test for masonry have been widely studied, leaving ultrasonic application to other fields.

2.1 Nondestructive testing background

Wave velocity and attenuation are affected by medium properties. Correlations exist between wave velocity and strength, stiffness, state of stress, and density of the medium. On the other hand, wave attenuation is a clear indicator of processes such as fracturing, cementation, decementation, and compaction. Mechanical waves can also be used to measure changes in wall thickness[ii] .

When the wavelength is significantly longer than the internal scale of the material, such as grain size, propagation parameters can be defined for the equivalent continuum. The shear and compressional wave velocities V_s and V_p are:

$$V_S = \sqrt{\frac{G}{r}} \qquad V_P = \sqrt{\frac{M}{r}} \tag{1}$$

where G is shear modulus, M is constraint modulus and ρ is mass density of the medium. The attenuation coefficient a is a measure of the decay of the signal amplitude per cycle. The attenuation coefficient can be expressed in terms of the wave amplitude at two different locations as function of frequency:

$$a = \frac{1}{\Delta f(f)} \ln\left[\frac{A_1(f)}{A_2(f)}\right] \tag{2}$$

where f is the frequency of the wave component, A_1 and A_2 are the spectral amplitudes at locations 1 and 2, and ?f is the phase difference for the given frequency.

Sonic stress-wave propagation methods are common procedures in NDT evaluations. However, the propagation mode, angle of excitation, and frequency content of the excitation have to be carefully selected for the results to be meaningful. Three common applications of NDT are impact echo, impulse response, transfer function, and spectral analysis of surface waves. A brief technical description of these methods follows.

2.1.1 Impulse response

The impulse response (IR) test requires a source with a built-in load cell to measure the input force. The response of the wall to the impact is measured with a transducer (accelerometer) held in contact to the wall close to the point of impact. The transfer function is computed between the impact force and the accelerometer response[iii]. The transfer function measures how each frequency component in the input signal is linearly modified to produce the output signal. This function is calculated in real time with a spectral analyzer. The localized resonant frequency of the structure is determined from the transfer function; this frequency is an indirect measurement of the wall stiffness. If wall thickness increases, the wall stiffness also increases, and an increase in the resonant frequency is expected. Therefore, the location of stiffer (thicker) sections can be inferred by comparing the resonant frequencies of different wall sections. Figure 2 summarizes a typical test setup. The resonant frequency of the first vibration mode is in the acoustic range, thus the equipment for this test should have a frequency bandwidth of 20 kHz.

2.1.2 Impact echo

In the impact echo (IE) method, two transducers are located on the same surface. One transducer sends a mechanical pulse (transmitter) through the wall and the second transducer "listens" (receiver). The time that it takes the pulse to travel from the transmitter to a reflecting interface and back to the receiver is used to compute the wall thickness, if the wave velocity of the medium is known. Figure 3 shows a simplified diagram of the test. Reflections can also be identified in the frequency domain. A transfer function is computed between the input and output signals (transmitter and receiver) with a spectrum analyzer. Reflections or "echoes" of the stress waves are usually indicated by distinct peaks in the transfer function. These peaks correspond to the frequencies with maximum reflection, which are mathematically related to the wall thickness[iv]. Scanning systems has been developed for the pulse velocity and the impact echo methods to replace point by point testing. Ultrasonic equipment is commonly required for this test because reflection frequencies are in the ultrasound range ($f > 20$ kHz).

2.1.3 Surface waves

The spectral analysis of surface waves (SASW) method is based on the fact that surface-wave velocity changes with frequency in a layered system. This frequency dependence of velocity is called dispersion. This dispersion is produced by the increase in penetration depth (wavelength) of surface waves with the increase in frequency. Thus, as the frequency increases the wave travels through shallower layers. The stiffness profile of a layered medium (e.g. wall-backfill) can computed from the measurement of surface-wave velocities for different frequencies. The test is performed by placing two transducers on the same surface at a distance Δx apart. The source is located at the same distance Δx from the first transducer. The two signals are recorded and transformed into the frequency domain using a spectrum analyzer to obtain cross-power spectrum, phase, and coherence functions. The surface wave velocity and wavelength can be computed from these functions [v vi]. A typical setup is shown in figure 4. To improve the results, several tests can be performed using different receiver spacings. This test requires wavelengths in the order of magnitude of the wall thickness. Therefore, acoustic equipment is required for wall thickness greater than 10 cm approximately.

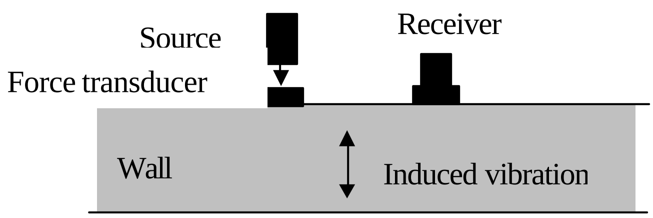

Figure 2: Impulse-response test method

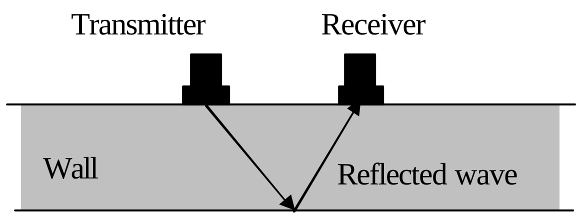

Figure 3: Impact-echo test method

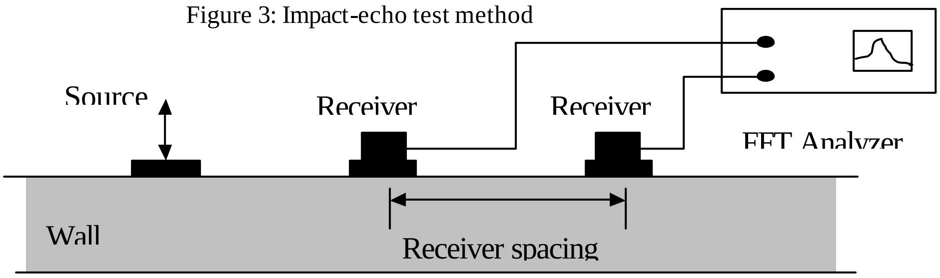

Figure 4: Surface wave test method

Wall thickness may be evaluated from field measurement according to the methodologies described for the IR, IE and SASW methods. A relative change in wall thickness can be detected from changes in the arrival time of reflections from the wall-backfill interface; this change in travel time is represented in figure 5.

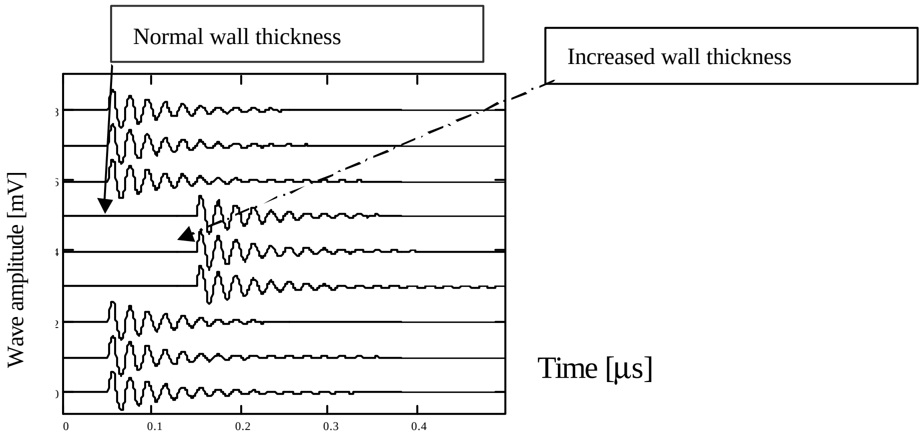

Figure 5: Example of change in travel time because of changes in wall thickness

3 MULTIPLE RECEIVER MEASUREMENTS

When mechanical energy is introduced to a medium, two types of waves are generated: body waves, which propagate spherically from the energy source, and surface waves, which propagate cylindrically from the source and are confined to the surface. Geometrical attenuation is smaller for surface waves than for body waves because the wave front is cylindrical and has a smaller area than the spherical wave front of body waves. Therefore, surface waves represent a convenient alternative for material characterization because they dominate the ground motion at any distance form the source.

The propagation of body and surface waves along the wall can be monitored with an array of transducers (figure 6). Multi-channel analysis of wave propagation (MAWP) allows the relative comparison of the structural condition of different sections of the wall. The better noise control, identification of higher modes of Rayleigh waves, and fast data collection are among the advantages of MAWP method. Two main parameters are measured: wave velocity and wave attenuation. The change in velocity is one of the most commonly used NDT methods. However, its isolated use for predicting material strength is limited because of the different variables that affect the strength-wave velocity relationship.

It is necessary to complement velocity data with independent information such as the change in attenuation and frequency content of the propagating pulse (frequency domain analysis).

The Fourier or frequency analysis of data collected from an array of receivers in a single test allows the calculation of the phase function for a given frequency with respect to distance. The greater the number of receivers used in a test, the higher the resolution of the results, thereby improving the ability to detect changes in the horizontal properties of the medium. Figure 6 shows a typical test configuration. From the time traces, the group velocities and the effect of reflections can be estimated. In addition, frequency domain records are used to compute phase velocities (dispersion curves) and attenuation ratios.

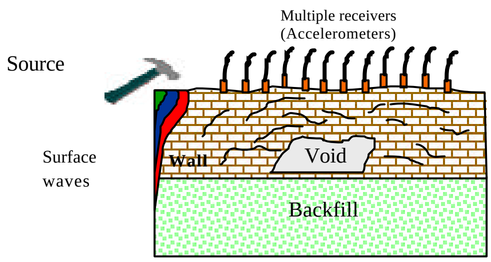

Figure 6: Example of multi-channel array of transducers

The location of the source and receivers has significant effect on the collected data[vii]. The distance between the source and first receiver determines the largest developed wavelength in the measurements; furthermore, it controls the near field effect. On the other hand, the distance between the transducers determines the smallest obtainable wavelength from the data. The source should produce enough energy in a wide frequency range.

The R-wave velocity (V_R) at any frequency (f) is related to distance (Δx) and the phase difference ($D f$) between the transducers, by the following relationship:

$$V_R = 2p\ f \frac{\Delta x}{\Delta f} \qquad (3)$$

Equation (3) defines the dispersion characteristics of the medium.

Figure 7 presents the attenuation of the maximum response in time and frequency, for a masonry wall length of 7.5 m.; this attenuation is quantified with the slope (a) of the linear curve fit shown for the first receivers (distance smaller than 3m). The comparison of section velocities and attenuation characteristics indicate that the low velocity and high attenuation could be due to internal fractures and weaker conditions of the brick and mortar.

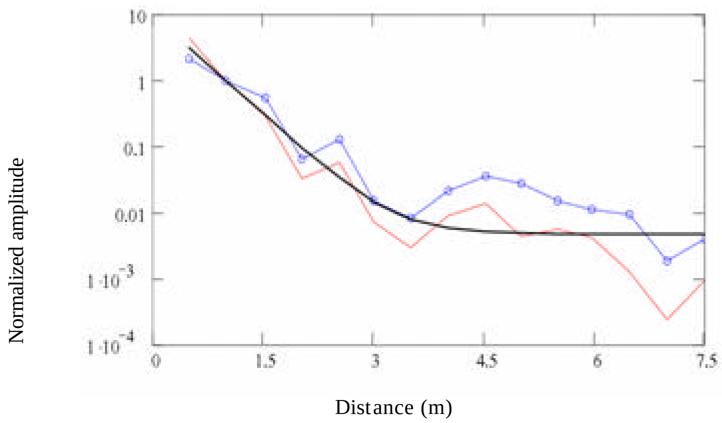

Figure 7: Normalized attenuation of maximum response in time and frequency

4 MAWP APPLICATION TO A STORICAL CANAL SIDE WALL

The application of MAWP test procedure on a retaining brick masonry wall, more than six meters high presenting at the top an out leaning of about 30 cm, is presented.

The retaining wall is a part of the Navigli canals side-wall downtown Milan. The Navigli canals history is strictly bound with the history and growth of the city itself, being now the entire remaining canals network under the responsability of the National Antiquities Authority. The structural restoration project had to garantee the static efficiency of the wall, mantaining at the same time the visibility of the actual ancient wall.

The data processing and results elaboration for field measurements has been based on the SASW method, during two different phases: the first phase, characterized by a more simple equipment, it was necessary for the basic calibration procedure, using information given by the nearby direct inspections. For example, it has been possible to check the resonance frequency from spectrum (figure 8) by calculating the thickness t of the wall according to the relation:

$$t = \frac{V}{2 \cdot f} = \frac{483}{2 \cdot 258} = 0.94\,m \qquad (4)$$

where V represents the velocity and f the frequency.

The value is very close to that calculated from the velocity of the S wave registered from the second receiver: both the calculated values are in good accordance with the result of the core-drill done in the vicinity.

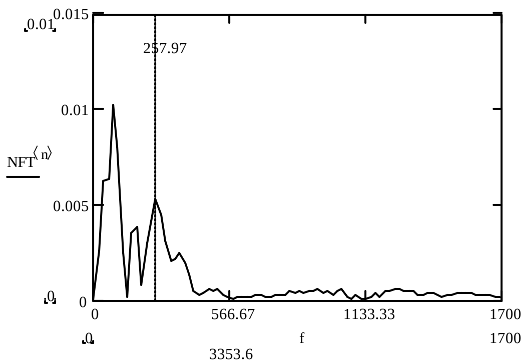

Figure 8. Fourier spectra for the signal of receiver 1

The second phase has been characterized by a more complete equipment, as shown in figures 9 and 10. This equipment is well suited for extensive field measurements (at least 12 receivers).

All the basic procedures, like the correct files data acquisition, the choosing of appropriate filter functions, the correctness of the complete traces pictures require deep experience, as well as in the successive elaboration step to define the range of frequencies f, the wave length λ, the disturbance frequency to erase.

At this stage, the files elaboration has been operated with the main goal of achieving, by calculating the attenuation coefficient α, information on grade of compactness in the wall section corresponding to each receiver.

Figure 9. Accelerometers installation

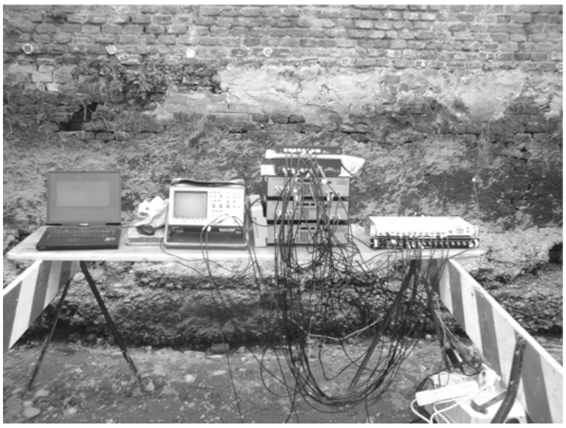

Figure 10. Data acquisition system

Mean values of the attenuation coefficient α have been detected for each section, as shown, as example, in Table 1, being the correlation between the wall material physical properties and the attenuation coefficient α, as mentioned before, as follows:

$$> \alpha \text{ value} \quad \Rightarrow \quad > \text{wall degradation}$$

Section	File	Alfa	Amp1	Amp2	Vp	Vs	freq0	freq1	freq2	Poisson	Side	Plates
1	Val01_2	0,52	9,233	2,521	1544	754	208	807	1148	0,34	left	15-1
2	Val10_1	0,25	6,04	4,5	1502	886	235	588	911	0,25	left	30-16
2	Val15_1	0,20	2,29	1,85	1860	1040	521	700	950	0,27	right	16-30
3	Val18_1	0,30	10,53	9,86	1880	1030	625	1000	1400	0,29	left	45-31
3	Val23_1	0,45	5,34	2,24	1980	1000	234	550	810	0,33	right	31-45
4	Val26_1	0,23	2,71	2,18	1856	930	391	900	1500	0,33	left	60-46
4	Val31_1	0,42	10,31	5,26	1975	950	650	910	1950	0,35	right	46-60
5	Val34_1	0,30	3,67	3,36	1945	930	547	970	1500	0,35	left	75-61
5	Val37_1	0,30	8,23	8,29	1844	930	390	1150	1875	0,33	right	61-75
6	Val42_1	0,34	10,44	7,81	2440	1206	600	1740	2450	0,34	left	76-90
6	Val45_1	0,34	10,51	8,24	2000	767	290	650	2050	0,41	right	90-76
7	Val50_1	0,28	5,00	3,74	1643	770	495	810	1460	0,36	Left	105-91
7	Val53_1	0,26	10,40	7,14	1674	823	625	810	2396	0,34	right	91-105
8	Val58_1	0,32	8,03	7,84	1709	880	755	1250	1590	0,32	left	120-106
8	Val61_1	0,25	13,67	5,27	1848	821	807	1320	1980	0,37	right	106-120
9	Val66_1	0,34	6,72	3,06	1523	910	338	650	1094	0,22	left	135-121
9	Val68_1	0,34	7,72	6,27	1771	837	650	1016	1823	0,36	right	121-135
10	Val69_1	0,35	4,11	4,43	1771	837	290	500	1000	0,36	left	149-136
10	Val72_1	0,30	0,41	1,27	1690	783	234	500	1200	0,36	right	136-149
11	Val78_1	0,24	1,66	1,27	1622	745	416	680	920	0,37	left	161-150
11	Val81_1	0,40	20,98	2,78	1623	714	312	650	1280	0,38	right	150-161

Table 1. Attenuation coefficient a for each section

From Table 1 one can read that sections 1, 3, 4, 11 are in worse physical conditions than the others; being these important suggestions for eventual filling intervention.

5 CONCLUSIONS

A campaign of sonic tests applied to a thick masonry wall was performed in parallel to core drills and excavations that gave direct information on actual geometry and consistency of the wall. The knowledge of these parameters allowed the selection of the best suitable sonic frequency and wave length to use for computing either a consistent velocity and wave attenuation, useful to obtain information on how to relate the sonic wave to the actual thickness and physical degradation of the wall. Multi-channel analysis of wave propagation (MAWP) allows for relating the structural condition of different sections of the wall by using the two main parameters: wave velocity and wave attenuation.

Nevertheless extensive applications of methods based on seismic wave propagation applied to masonry still need more calibration experiences, in the field of a better interpretation of the different signals.

ACKNOWLEDGEMENTS

The authors acknowledge the regional and civic administrations for their continous assistance, and Andrea Bonizzi, graduate student, who helped in the data collection.

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