RELATIVE NDT EVALUATION OF THE SIDE WALLS OF A BRICK CHANNEL

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Abstract

The network of channels called Navigli was built in the surrounding country and downtown Milan, Italy. Wave propagation measurements were taken along the channel for a total length of 80 m. Each test consisted of the simultaneous measurement of the response of the wall with 15 transducers to an impulse load. The relative condition of the wall is evaluated by considering three main wave characteristics: group velocity, phase velocity, and attenuation coefficient. A fuzzy logic model is developed to make a relative evaluation of the condition of the sidewall.

Introduction

The evaluation of the condition of existing structures is a key element in the maintenance and safety plans of any municipality. This evaluation should be based on realistic measurements of different variables such as geometry and material strength. These variables are commonly 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 normal operations. Wave velocity and attenuation depend on the stiffness and mass of the medium, thus variations in the medium properties should be inverted from the change in wave parameters.

The Navigli channel was mainly built during the XVI century. The current civic administration is facing the difficulty of saving what remains of these complex hydraulic and historic structures. Typical cross-sections of the wall are shown in Figure 1. The restoration of the Navigli should be performed without causing mayor disturbance to this historic structure. Therefore, the use of non-destructive methods for the condition assessment of the channel is an ideal and cost-effective solution. The pulse velocity method is widely used for the assessment of the quality of concrete; this assessment is based on empirical correlations between wave velocity and strength (Popovics and Rose 1994, Ronca 1993). Geophysical methods commonly used for site characterization are seismic reflection or refraction, spectral analysis of surface waves, seismic crosshole and downhole, ground penetrating radar, resistivity, and electromagnetic survey. On the other hand, the spectral analysis of surface waves (SASW) method has been proposed for the evaluation of shear wave profiles in layered media (Nazarian et al. 1988, Rix et al. 2002).

This paper summarizes the results of the nondestructive testing programme performed on the sidewalls of the Navigli channel. Wave propagation measurements were taken at two different elevations on the sidewall (bottom and top lines). All the results presented in this paper correspond to the bottom line only. The response of the wall was measured at 161 locations; the transducers (accelerometers) were spaced at 0.5 m, the total length of wall tested was 80m, and the total number of tests performed was 86. Each test consisted on the simultaneous measurement of the response of the wall on 15 transducers, thus each test covered a section of 7.5 m in length. The relative condition of the wall is evaluated by considering three main wave characteristics: group velocity, phase velocity, and attenuation coefficient. The sections that showed low values of group and phase velocities and high values of the attenuation coefficient are identified as the weaker sections. In the following sections, the theory of the techniques used for data analysis is presented, and then the experimental setup and the testing programme are described. Finally, the main results and conclusions from the testing programme are outline.

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Background

The data collected from seismic tests can be analyzed in both time and frequency domains. In the time domain, group or pulse velocities are evaluated; whereas, phase velocities and the attenuation coefficients are evaluated in the frequency domain. Wave velocity is related to the strength, stiffness, state of stress, and density of the medium. On the other hand, wave attenuation is an indicator of fractures, cementation, de-cementation, and compaction.

Figure 1. Typical cross-sections of the sidewall

The propagation of low-strain mechanical waves is a perturbation phenomenon that assesses the state of materials without causing permanent effects. When the wavelength is larger than the internal scale of the material, such as the brick size in a masonry wall, the wave velocity and attenuation coefficient can be defined for an equivalent continuum. The group shear and compressional wave velocities V_S and V_P are (Graff 1975):

$$V_S = \sqrt{\frac{G}{\rho}} \qquad V_P = \sqrt{\frac{M}{\rho}}$$

where G is shear modulus, M is constraint modulus and ρ is mass density of the medium. The velocities of compressional waves and shear waves are related through Poisson's ratio of the medium. If the medium is homogeneous, all the frequency components of a pulse travel at the same speed V_S or V_P. However if the medium is dispersive, the propagation of each frequency component has a different velocity. The velocity of the pulse is referred to as group velocity; whereas, the velocity of each frequency component is called phase velocity.

For low excitation frequencies, two thirds of the energy introduced into a medium from a circular rigid plate converts to surface waves (Richart et al. 1970). In conventional seismic surveys, surface waves are not used because they mask the reflection and refraction events from body waves. The use of surface waves for shallow applications has been improving since the development of the spectral analysis of surface waves (SASW) method. The depth of penetration of surface waves is proportional to the pulse wavelength. Surface waves practically penetrate to a depth of two times their wavelength. However for material characterization, their effective depth of penetration is approximately one-third their wavelength because the maximum displacements induced by surface waves take place close to the surface. The phase velocity of Rayleigh waves (R-wave) velocity V_{ph} at any frequency f is related to distance Δx and the phase difference $\Delta\phi$ between the receivers by:

$$V_{ph} = 2\pi f \frac{\Delta x}{\Delta \phi} \qquad [1]$$

The wavelength λ as a function of frequency and phase velocity is given by

$$\lambda(f) = \frac{V_{ph}}{f} \qquad [2]$$

As seismic waves propagate, their amplitude decreases with distance due to geometric spreading of the wave front and the intrinsic attenuation of the medium. Geometric attenuation is the result of the increasing surface area of the wave front as it propagates outward. In an ideal material, the amplitude of the wave front decreases only due to geometric spreading because the intrinsic attenuation is zero. However, in real materials, part of the elastic energy is absorbed. Intrinsic attenuation can be expressed as

$$\frac{A_2}{A_1} = e^{-\alpha\left(r_2 - r_1\right)} \qquad [3]$$

where α is the attenuation coefficient, the wave amplitudes at distances r_1 and r_2 from the source are A_1 and A_2, respectively.

The two-dimensional Fourier transform (2D-FFT) has been used to compute dispersion curves of multimode signals (Zerwer et al. 2001). The arrangement of multiple-channel measurements into a matrix permits the use of the 2D-FFT, which generates a matrix of complex numbers. The contour plot of the magnitude of the 2D-FFT renders a plot of frequency versus wavenumber $k = 2\pi/\lambda$. Different waves are identified in the contour plot as a sequence of peaks. Peaks associated with non-dispersive waves plot as straight lines that pass through the origin; whereas, peaks corresponding to dispersive waves plot as curved lines with non-zero intercepts. Positive wavenumbers represent waves traveling in the forward direction (away from the source); whereas, negative wavenumbers represent waves traveling in the backward direction (towards the source).

Fuzzy-based methods have increasingly been used in a variety of civil and infrastructure-engineering problems from the evaluation of concrete and steel structures to water and wastewater applications (Liang et al. 2001; Najjaran et al. 2004). Fuzzy logic provides a language with semantics to translate qualitative knowledge into numerical reasoning. In many problems, the available information about the likelihoods of various items is vaguely known or assessed; hence, the information in terms of either measured data or expert knowledge is imprecise to justify the use of deterministic numbers. The strength of fuzzy logic is that it provides a rational and systematic approach to decision making through the integration of descriptive knowledge (e.g., very high, high, very low, low) and numerical data into a fuzzy model and uses approximate reasoning algorithms to propagate the uncertainties throughout the decision process. A fuzzy model contains three distinguished features: fuzzy numbers instead of, or in addition to numerical variables; relations between the variables in terms of IF-THEN rules; and an inference mechanism. A fuzzy number describes the relationship between an uncertain quantity x and a membership function $\mu(x) \in [0,1]$. A rule base determines the relationships between the inputs and outputs of a system using linguistic antecedent and consequent propositions in a set of IF-THEN rules. The inference mechanism uses approximate reasoning algorithms and the relationships to infer the outputs for given inputs.

Experimental methodology

The sidewall of the Navigli channel was instrumented at 2 m from the base of the channel. Steel plates at 0.5 m spacing were attached to the wall with epoxy resin. Measurements were obtained from 161 points (total length L= 80 m). The wall was divided into 11 sections: ten sections of 7.5 m and the last section of 5 m long. The length of the sections was limited by the number of channels of the data acquisition system (15 channels). The accelerometers were glued to the steel plates to conduct different multichannel surface wave tests (MASW). For each MASW test, 15 traces were recorded; each trace contained 2400 data points. After testing one section, the accelerometers were moved to the next section. A one-pound hammer was used as a source to make an impact at three locations, i.e., right, center and left of the array of accelerometers. Depending on the attenuation of the wall, the source was located at least at two different horizontal distances from the first receiver.

The equipment used in all the tests (Figure 2) consisted of a digital oscilloscope (HP 35610A), four filter-amplifiers (Krohn-Hite 3984), impulse hammer (Dyatran), 15 accelerometers (PCB and Dytran, frequency range 1 Hz to 5 kHz), and a laptop-based data acquisition system of 16 bit resolutions and 1 MHz maximum sampling rate (Iotech, Wavebook E16). The sampling rate used was 62.5 kHz per channel; thus, a maximum frequency of 6.25 kHz can be recognized from the time signals and a maximum frequency of 31 kHz can be identified from the Fourier spectra. The time window was 38 ms; the frequency resolution in the spectra was 26 Hz. The time responses are 2D-Fourier transformed to determine spatial and temporal frequencies from the contour plots in the frequency-wavenumber space.

Results

Each time signal is corrected by the amplification and sensitivity factors used in the field for each accelerometer. The corrected data is used to calculate the attenuation factor. However, the data is also normalized to the maximum response of each trace to enhance the interpretation of time traces and Fourier spectra. Time signals are significantly affected by noise after the eighth receiver because of the attenuation properties of the sidewall. Therefore, the responses of the accelerometers located in the first four meters of the array are given more weight in the data analysis. The arrival times are used to compute the corresponding group velocities (V_P and V_R). The arrival of compressional waves is weak because of the low amplitude of the generated p-waves and the attenuation properties of the sidewall.

The Fourier spectra indicate that after the first receiver the energy is mostly distributed between 250 Hz and 2,500 Hz; these frequencies correspond to wavelengths equal to λ=1.45 m and λ=0.30 m respectively. Therefore, the measured properties of the sidewall are representative of depths of 10 cm to 50 cm. Frequencies between 1 kHz and 4.5 kHz attenuate faster than frequencies below 1 kHz. Phase wave velocities change with distance because of the different conditions of the sidewall. Phase velocities are computed by curve fitting the change in phase angle with distance (Eq. 1) for each frequency component. A decrease of phase velocities with frequency indicates that the condition of the inside sidewall (0.50 m to 1.0 m) is better than the condition at the surface (0.0 to 0.25 m). Phase velocities give an indication of the relative condition of the sidewall with depth; however, the results should be interpreted carefully because wave reflections influence significantly the results. Cracks and voids reflect and diffract the wave front, thus relatively higher wave attenuation is expected in weaker sections than in sound sections. The attenuation or absorption coefficient (α, Eq. 3) can be computed in terms of the maximum response in time, frequency, or the area of the Fourier spectra. The attenuation information confirms previous observations that after the first 3.5 m of the array signals are drastically affected by the noise and wave reflections because the wave amplitude does not continue to decrease with distance in the second half of the array.

Two-dimensional Fourier transforms indicate wave velocities (V_R and V_P) that are closed to the measured group velocities. Energy peaks for negative wavenumbers indicate spatial aliasing for frequencies higher than 1300 Hz. The spatial aliasing is produced by the selected receiver spacing (Δx= 0.5 m). Spatial aliasing can be reduced by using a smaller spacing; however, this solution requires an increased number of measurements and thus more time for testing and data processing. The surface-wave group velocity (V_R), range of phase velocities (V_{ph1} to V_{ph2}), attenuation coefficient (α), and the frequencies of higher spectral energy (f_l) for all sections are summarized in Table 1. The average values for these variables are shown at the bottom of the table. Results for the right-hand side and the left-hand side of the sections are denoted by the letters R and L, respectively. The condition of the sidewall could change in a distance of few meters; therefore, it is possible to have consecutive sections with completely different conditions (e.g. sections 1L and 2R, Table 1).

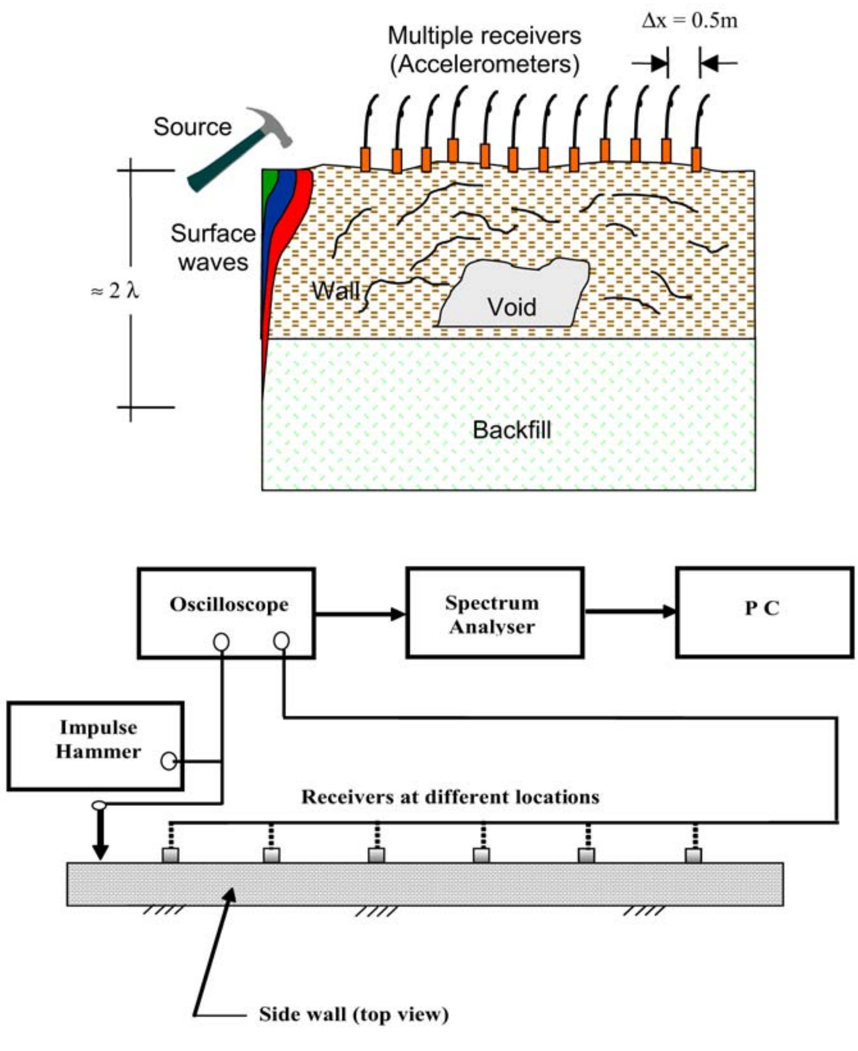

Figure 2. Test configuration of a multiple-channel seismic measurement

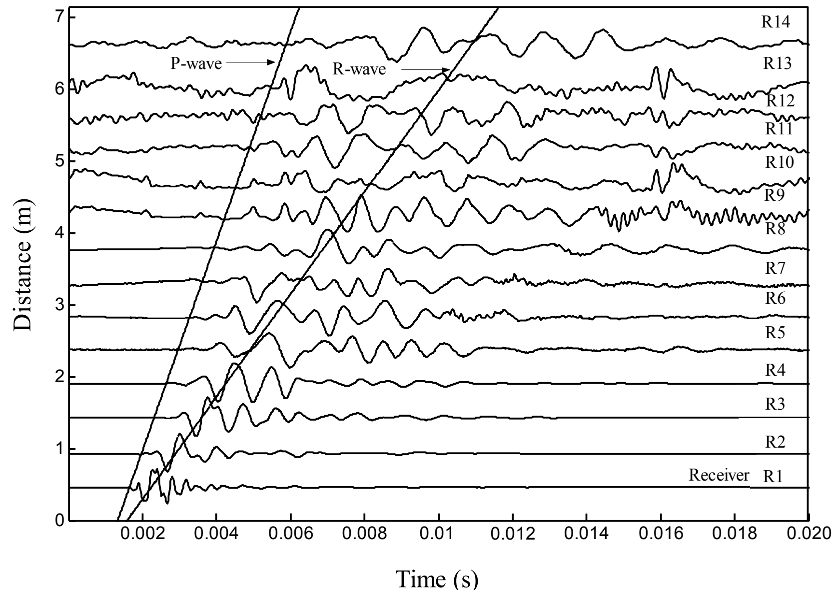

Figure 3. Typical time responses (Section 1). Solid straight lines indicate the arrival of compressional waves (p-waves) and surface waves (r-waves)

A fuzzy model is developed to assess the relative structural condition of different sections of the brick sidewall using seismic wave properties. The fuzzy model summarizes the results of nondestructive measurements in a quantitative parameter named condition index (CI). The most straightforward fuzzy modeling method is the direct approach in which expert knowledge is used to specify input and output variables (e.g. group velocity, phase velocity, wave attenuation, and condition index). Specific steps are: (a) to label the partitions of the input and output variables with linguistic terms (e.g. low, medium, high); (b) to define a set of linguistic rules (IF-THEN) that represent the relationships between the variables; (c) to select an appropriate reasoning method; and (d) to verify the model. A condition index CI = 0 indicates a section in relatively very good condition; whereas, CI = 1 refers to a damaged section. The input variables are partitioned into three fuzzy numbers low (L), medium (M), and high (H). The output is expressed using five partitions: very good (VG), good (G), moderate (M), deteriorated (DT), and damaged (DG). A fuzzy expert system (Najjaran et al. 2004) is used to develop the fuzzy model and evaluate the condition indices for the different sections. The results are summarized in the last two columns of Table 1. The condition index shows that Sections 1L, 6R, 8R, 9L, 10R, 10L, 11R and 11L are the relatively weaker sections. Visual inspection of these sections revealed that surface conditions are fine for most of them; however, voids and cracks are evident close to the line of measurement. In addition, low velocity and high attenuation could be the result of internal cracks and weaker conditions of the brick and mortar that could not be evident on the surface.

Conclusions

MASW tests were performed on 11 sections of the Navigli channel to assess the relative condition of the sidewall. The minimum and maximum group shear wave velocities were Vs=667 m/s and V_R=1200 m/s whereas the minimum and maximum shear wave phase velocities were V_{ph}= 500 m/s and V_{ph}=1140 m/s. The frequency with higher energy varied from 500 Hz to 1600 Hz; thus the penetration of surface waves was enough to reach the back surface of the sidewall (approximately at 1m from the surface of the wall).

A fuzzy model is developed to compute a condition index as a function of the group velocity, the maximum and minimum phase velocities, the frequency with higher energy in the Fourier spectrum, and the attenuation coefficient of each section. The condition index shows that Sections 1L, 6R, 8R, 9L, 10R, 10L, 11R and 11L are the weaker or less stiff sections of the sidewall. Visual inspection of these sections revealed that surface conditions are fine for most of them. However, voids and cracks are evident near the array of transducers. In addition, low velocity and high attenuation could be the result of more severe defects such as internal fractures and weaker conditions of the brick and mortar that could not be evident on the surface.

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Table 1. Field data and calculated condition index (CI)

Section	V_R m/s	V_{ph1} m/s	V_{ph2} m/s	f_1 Hz	α	Condition Index	Condition State
1R	N/A	N/A	N/A	N/A	N/A	N/A	N/A
1L	754	800	600	700	0.55	0.917	**Damaged**
2R	1040	800	600	800	0.20	0.000	**Very Good**
2L	870	870	540	588	0.25	0.582	**Moderate**
3R	1000	1140	850	550	0.45	0.500	**Moderate**
3L	1030	880	700	1000	0.30	0.250	**Good**
4R	950	625	400	910	0.42	0.429	**Moderate**
4L	930	1000	600	900	0.23	0.250	**Good**
5R	930	730	430	1150	0.33	0.437	**Moderate**
5L	930	930	600	1100	0.33	0.311	**Good**
6R	767	750	600	650	0.56	0.917	**Damaged**
6L	1200	1000	600	1600	0.34	0.155	**Good**
7R	820	870	790	900	0.26	0.424	**Moderate**
7L	770	810	720	810	0.28	0.500	**Moderate**
8R	787	800	700	850	0.38	0.625	**Deteriorated**
8L	880	836	766	1150	0.40	0.465	**Moderate**
9R	837	800	600	1016	0.34	0.478	**Moderate**
9L	910	700	300	650	0.34	0.558	**Moderate**
10R	783	500	400	500	0.38	0.750	**Deteriorated**
10L	837	500	400	500	0.38	0.652	**Deteriorated**
11R	667	580	400	650	0.65	0.917	**Damaged**
11L	745	745	500	660	0.20	0.750	**Deteriorated**
Average	878	802	601	840	0.36	0.500	**Moderate**

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