The historic side-walls of the Navigli canals in Milano: in situ and laboratory tests for the structural conservative project

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ABSTRACT: The paper gives significance at first to an historic overview of the origin and development of the network of the Navigli canals, strictly related to the history and growth of Milano itself. Focusing the architectonic and historical meaning of the today remaining canals, the significance of the salvage of the related structural components is underlined. The calibration procedure of some different in situ and complementary laboratory tests on the side walls in a "pilot site work", and, subsequently in different positions, where the first rehabilitation site work has been open, are described. The aim is of suggesting a guide line for the conservative rehabilitation project of the ancient masonry walls, under those specific physical conditions and requests of the Antiquities National Authority, that are similar to those which may be found in citadels walls or even in the different structural components of the masonry arch bridges.

1 HISTORIC OVERVIEW

The Milano’s city history is strictly bound to the geographical history of rivers and water routes, characterizing, since at least the Roman time, geological configuration of the northern Italy's land. Figure 1 testifies of the hydro-network (canals and rivers) surrounding Milano during the last centuries of the Roman empire. The three concentric lines define the city border, starting from the center part, of Roman, medieval (about XIII century) and Spanish period (XVII century), all characterized by water defense ditches, that became navigable canals.

Through rivers and canals, Milano became, since the XIV century, one of the most important commercial venue with Switzerland. The commercial harbor downtown Milano had his major development during XVI and XVII centuries, with a network of Naviglis crossing the town and reaching even the boundary of the Venetian Republic. Milano developed its peculiar attitude of commercial city, thanks mostly to this hydraulic network.

The problem of different levels among lakes, rivers and the Milano’s harbor (even 56 meters) was solved with a system of locks, some of them designed by
Leonardo da Vinci (Fig. 2). The lock called “Conca dell’incoronata”, built according to the engineeristic suggestions of Leonardo, was visible in its overall complex hydraulic system until some decades ago, see Figure 3.

The Navigli network reached its largest extension, more than 250 km, during the nineteenth century; many nobiliary villas and powerful monasteries were built near the sites of the Navigli and they are still standing today. During the last decades of the XIX century, mainly because of the railway development, the commercial appeal of the Navigli declined.

The landscape in the surrounding and downtown Milano were indubitably characterized by the crossing Navigli water route network, whose memory are the actual numerous toponomastic names; the pictures in Figures 4 and 5 recall the views of the today streets, still called “via Laghetto” (small lake street) and “via della chiusa” (lock street). The first decades of XX century are testimony of a city crossed by numerous arch bridges, even with important decorations (see Figure 6 “ponte delle sirene”). Starting from the forties, the works of covering the water canals downtown Milano began, destroying even hydraulic plants, as shown in Figure 7.
2 ACTUAL REMAINING HYDRAULIC STRUCTURES

During the first half of the XX century, due to the increasing need of car routes, the Naviglis downtown Milano were covered destroying many hydraulic plants, as was the main part of the harbor. What remain inside Milano of these canals now is under the Conservation Architectural Authority. In the last 20 years the both sides of the Naviglis still crossing the city became the artistic quarter and a live commercial and tourist attraction, like happened in many European cities, see for example the restored locks and canal of Figure 8, in central London.

But, since many decades, the maintenance of the structural components, like foot-arch-bridges, locks and most of all side walls was abandoned, living the structures in very unsafe conditions. Moreover, intensive building constructions, increasing in the cars and busses traffic, progressive excavations for civic services worked together against the safe of stability of the side walls, in particular those of the canal called Naviglio Grande, being its structures the most ancient.

Scarce are the documents describing the building techniques of the side walls. It is possible to suppose that only at the end of XVIII century the compacted soil banks confined by wooden piles, have been in some parts renewed using stones or even brick masonry. Only from the beginning of XIX century (Napoleon period) the maintenance of the side walls started with the use of cementitious mortar to bound the bricks (Celona & Beltrame 1982, Maffei 1984, Bruschetti 1972). Actually the static interventions were sporadic and limited, giving the results at present visible: the walls are a patchwork of different materials and construction techniques, as it is shown, just an example, in Figure 9.

The ancient walls are mostly hidden; moreover there is no written documentation of the material, geometry and type of foundation used. From the archives, it is possible to guess that the brick or block section of the
The problem of knowing the actual geometry was first analyzed by computing the minimum dimensions required to guarantee the equilibrium of the wall as it is summarized on Table I. This Table takes into account different geometries for a simple rectangular cross section gravity wall, in terms of height H and width b, and for the soil properties (specific weight $\gamma_s = 20 \text{ kN/m}^3$ and friction angle $\phi_s = 30^\circ$). A specific weight of the masonry $\gamma_m = 18 \text{ kN/m}^3$ has been assumed, and a live load $q = 10 \text{ kN/m}^2$ has been applied. According to different cases, the capacity of the wall versus the external actions in terms of the resisting $M_R$ and applied $M_S$ moments are shown in the last two columns. These simplified calculations clearly show the minimum level below which equilibrium conditions can not be satisfied, moreover hypothesizing compact material inside the wall.

Because it is impossible to use large and deep excavations all along the wall, unless traffic is restrained in a large section of the town, and also because of...
the presence of a network of active underground civic services, it was decided to perform a program of in situ and laboratory tests with the double aim of either achieving better characterization of the actual local geometry and physic and mechanical properties, either optimizing the calibration procedures of non destructive tests, in particular those based on radar and sonic principles.

3 IN SITU AND LABORATORY TESTS

A program of in situ and laboratory tests has been performed with the double aim of better characterization of the actual geometry and the mechanical properties of the wall under consideration. The following tests were performed and mutually related (Bonizzi 2003) during the spring period without water in the channel: localized excavations in the inner part of the side-wall, geotechnical boreholes, core-drills, endoscopic inspections and laboratory test for the material characterization. It was immediately clear that the results of radar technique were unreliable because of the persistence presence of water in the walls and in the surrounding soil, as it was confirmed also by the laboratory tests on mortar and bricks.

Here just some significant results are reported and correlated, for their correct implementation and useful indications for the best structural conservative rehabilitation project.

The most significant discovery obtained from the campaign of the in situ tests can be summarized as follows:

- not only the material, but also the width of the wall is mostly variable;
- generally foundations are absent, or, at least, the wall is provided by a limited enlargement.

The tests on material samples, based on X ray techniques, termogravimetry, PH measurement and more chemical and mechanical analysis are reported on Mapei (2003). Here we just underline the material physical properties found, strictly correlated with the mechanical properties:

- the mortar presents no more cementitious component;
- high porosity either for the mortar as for the bricks (Figs 13, 14);
- high water absorption;
- average mechanical good conditions for the bricks;
- low presence of soluble salts, as the consequence of a wash out process.

A campaign of sonic tests was performed and calibrated by using small nearby 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 a consistent velocity, which is the basic parameter for defining the possible thickness and the average matic consistency of the wall. As a matter of fact, wave attenuation is useful to obtain information on how to relate the sonic wave to the physical degradation of the wall. As it is known, sonic techniques to characterize a medium properties are successfully used in the case of metallic material or for detecting underground discontinuities. In the case of brick masonry, the method has been tested and calibrated in the field and in laboratory prototypes, mostly in the last decades. As it was shown (Ronca 1993, Ronca 1995) by testing samples constructed with pre-established percentages of voids in the mortar layers, the methods using ultrasonic frequencies are not best suited to detect small voids, frequently present in the walls of historic buildings, which are responsible of consistent reductions of mechanical properties of masonry structures.
The use of sonic tests in the low frequency range, it has proved to be more useful for material characterization, because of its lower attenuation, for detecting even small physical imperfections.

Nevertheless reliable 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. With this research mood, the sonic tests have been carried out on the Naviglis sides walls, as an unusual and great possibility.

Multi-channel analysis of wave propagation (MAWP) allows the relative of the structural condition of different sections of the wall (Zerwer et al. 2001, Ronca et al. 2004). The better noise control, identification of higher modes of Rayleigh waves, and fast data collection are the among 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.

Wave velocity alone does not provide complete information of structural condition; therefore it is necessary to complement velocity data with independent information such as the change in attenuation and frequency content of the propagation pulse (i.e. operating in the frequency domain analysis). In some cases, wave velocity could be almost constant, whereas wave amplitude could change significantly because of the medium attenuation characteristics.

The results presented in the paper for field measurements and data processing 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 (Fig. 15) by...
calculating the thickness $t$ of the wall according to the relation:

$$t = \frac{V}{2 \cdot f} = \frac{483}{2 \cdot 258} = 0.94 \text{m}$$

(1)

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.

The second phase has been characterized by a more complete equipment, as shown in Figures 16, 17 and 18. This complete equipment is well suited for extensive field measurements.

![Figure 19. Acquired traces.](image)

Table 2. Attenuation coefficient $\alpha$ for each section.

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<th>Section</th>
<th>Side</th>
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<th>$Amp_1$</th>
<th>$Amp_2$</th>
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<th>$V_s$</th>
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All the basic procedures, like the correct files data acquisition, the choosing of appropriate filter functions, the correctness of the complete traces pictures (as for example shown in Figure 19) require deep experience, as well as in the successive elaboration step to define the range of frequencies $f$, the wave length $\lambda$, 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 $\alpha$, information on grade of compactness in the wall section corresponding to each receiver.

Mean values of the attenuation coefficient $\alpha$ have been detected for each section, as shown, as example, in Table 2. Being the correlation between the wall material physical properties and the attenuation coefficient $\alpha$ as follows:

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

From Table 2 one can read that sections 1, 3, 4, 11 are in worse physical conditions than the others, important suggestion for eventual filling intervention.

4 CONCLUSIONS

The problem described in the paper illustrates the difficulties of approaching a functioning historic structure, showing external heavy visible damage, but with particular features that make the geometric and materic relief almost impossible, like are the masonry side walls of water canal net and related plants inside a...
city. Non destructive tests can be used with the aim to determine the realistic value of parameters, such as shape, homogeneity and actual thickness of walls that have been built or reconstructed during the centuries. For these purposes a coordinated in situ and laboratory tests have been implemented, with a focus on calibration procedures of sonic wave propagation technique.

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