Monitoring of Vibrations for the Protection of Architectural Heritage

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MONITORING OF VIBRATIONS FOR THE PROTECTION OF ARCHITECTURAL HERITAGE

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ABSTRACT

A peculiar aspect in Structural Health Monitoring is concerning the monitoring of vibrations in urban environments that may affect the integrity and conservation of architectural heritage buildings. The paper reviews the main issues on the subject and takes into consideration the problem of measuring and interpreting vibrations in buildings. The use of numerical models is also discussed and a practical case study is finally presented.

KEYWORDS : *Structural Health Monitoring, vibration measurements, interpretation models, historical buildings.*

INTRODUCTION

A peculiar aspect in Structural Health Monitoring is concerning the monitoring of vibrations in contemporary urban environments that may affect the integrity and conservation of architectural heritage buildings. This aspect is not only important in Southern European countries, and namely in Italy where the majority of historical and monumental buildings is concentrated, but also has become an issue of general interest.

As a matter of fact, the development of urban mobility, including private and public traffic on roads, urban railways and metro systems, together with the construction activities that continuously are taking place in modern cities, is generating complex wave patterns in the ground that transmit to the buildings causing effects that still remain partly unclear.

A number of standards have been more or less recently released, covering the aspects of vibration measurements and stating acceptability limits for the vibration intensity. However, established limitations are not uniform, basically depending on the characteristics of affected building types and, also, the distinction between structural damage induced by vibrations and damage to non-structural and decorative components is often unclear.

The paper will first review the main issues of the subject, discussing the different standards. The main focus of the paper will be however concentrated on the measurements and interpretation of the vibrations in buildings, especially taking into consideration acceleration versus velocity data.

Due to the complexity of the wave patterns, interpretation of the wave propagation from vibration sources to buildings and from foundations to top floors is not simple and cannot be based on acceleration or velocity measurements only. The use of numerical wave propagation models in the ground and of simplified building dynamic models will be also discussed, outlining the need for a very careful engineering design of the instrumental monitoring system and for the development of reliable source and propagation models. The discussion will be supported by a numerical example and by an experimental case study.

1 AMBIENT VIBRATIONS AND HISTORICAL BUILDINGS

In contemporary urban areas several sources of vibration are transmitting waves to buildings. Waves are transmitted through air, producing noise, and through the ground to building foundations and from foundations to the upper floors. The majority of vibration sources are related to road traffic, metro systems and trains but construction activities, like pile driving and excavation by mechanical tools or blasting are important vibration sources as well. In addition to external vibration sources, in modern buildings internal vibration sources should be considered, like the presence of rotating machines, air conditioning systems and human activities. Noise and vibrations produce disturbance to building occupants, inducing anxiety and sometimes physical diseases but mechanical vibrations may also produce damage to building components. Therefore, the study of the phenomenon has received significant attention by scientists and engineers in the last several decades and lawmakers or regulatory agencies of many different countries have released various standards to limit the intensity of vibrations that human activities and transportation systems are allowed to release to environment.

The phenomena of wave generation from sources and the propagation from sources to receptors are however very complex and depend on a number of parameters difficult to categorize. For example, vibrations caused by road traffic are influenced by the characteristics of the vehicles and by the surface conditions of roads; wave propagation in the ground is influenced by ground conditions and when the waves reach the foundation of a building, the transmission of vibrations to the upper part of the building is influenced by the dynamic characteristics of the building itself. Because of that, limitations on the vibration intensity can only be stated at receptors. Recent experimental and theoretical studies aimed at characterizing the vibratory phenomena caused by traffic, construction activities, explosions and their effects on buildings can be found for example in [1-6].

The main concern of the present paper is however related to the effects that external sources of vibration may produce on historical buildings and, in particular, to buildings representing a significant architectural heritage. An old paper by Rainer [7] presents an interesting discussion on the subject, outlining the following points:

- vibrations are most frequently blamed for deterioration of historic buildings while other detrimental effects are apparently ignored;
- historic buildings may not be structurally sound and materials degradation may already have been taking place;
- even small damages (cosmetic) may be very significant for both monetary and non-monetary values;
- a distinction shall be made between short-term and long-term effects, as the latter could gradually produce damages also for very low vibrations intensities;
- degradation phenomena due to long-term vibrations are not well known.

Long-term vibrations are usually associated to traffic in urban roads. As a matter of fact, very few cases have been reported in which traffic vibrations have been clearly associated to damages in monumental buildings. One of such cases is perhaps the Villa Farnesina in Rome [8].

Nonetheless, monitoring of vibrations is considered to be a very important issue for the protection of architectural heritage because it allows disclosing of damages in the long run and eventually correlating damages to low-intensity steady vibrations, as indicated in [9].

It has to be noted that frequent transit of heavy vehicles and construction works may induce vibrations largely exceeding the intensity of those caused by normal traffic and therefore may be responsible for damages beyond cosmetic level and also involving secondary or main structural components. Careful monitoring of such phenomena is of a paramount role for the protection of architectural heritage buildings.

2 VIBRATION STANDARDS

As already noted, several standards have been released in different countries to set limits to the vibration intensities recorded at significant reception points in buildings. Modern standards address the methods to be used to select and properly locate the instrumentation, to measure vibrations and to process measurement data. The reference parameter to measure the intensity of vibration is usually the peak particle velocity (PPV) and limits are stated for various ranges of the dominant excitation frequencies and different building types, according to their different structural characteristics.

A widely accepted standard for the measuring of vibrations in buildings is the ISO 4866 standard [10]. Most of the national standards comply with ISO 4866 but suggested limits of acceptability may differ substantially among the various documents, especially as concerning ancient buildings. Indeed, the structural characteristics of these buildings are very different from one country to another. Some standards are based on experimental campaigns performed on typical buildings while some others refer to limits stated in other countries. For example, the recently revised Italian UNI 9916 [11] include as reference the limits stated by the German DIN 4150. This reference proposes different limits for short-duration and for long-term vibrations in terms of PPV (horizontal) and is considered to be conservative also for the typical historical buildings existing in Italy.

Other standards or studies related to standards, besides stating limits on the PPV, also propose for special cases limits on the peak acceleration or on the peak displacements. This is an interesting issue because velocities are proportional to strains and accelerations are proportional to forces. The selection of the reference parameter can be made dependent on the measuring instrumentation and on the methods used to interpret to response of the building or building component.

Modern MEMS-based instrumentation and data transmission protocols, including wired and wireless communications, allow effective and cheap measurement of acceleration time histories. Velocity time histories can be obtained by on-line or off-line numerical integration. Strain time-histories may also be directly obtained. Miniaturization of sensors also allows measurements of accelerations and strains to be taken directly on the sensitive parts of the buildings (e.g. stucco decorations or painted surfaces).

3 INTERPRETATION MODELS

To really take advantage of the capabilities offered by modern instrumentation in vibration monitoring of architectural heritage buildings, various data interpretation models can be used. The use of such models is of particular interest when vibration sources are non-conventional or when the vibration intensity limits suggested by the reference standards are not considered appropriate to the characteristics of the site.

With reference to typical problems like the prediction of pile-driving or blasting vibrations, the existing models can be divided into four main categories depending on their approach:

- *Empirical models* – based on empirical knowledge from former measurements and experience of piling works;
- *Theoretical models* – based on theoretical knowledge usually consisting of numerical models;
- *Engineering models* – a mix of empirical, theoretical and engineering knowledge (sometimes also called mixed-approach models);
- *Intelligent Science models* – based on artificial intelligence (AI) techniques.

Current empirical models have the advantage that they are easy to use and require relatively small amounts of input data, however, they cannot be considered reliable (often they tend to highly overestimate the vibration level). Today's theoretical prediction models seem to be somewhat more reliable, but instead they require great amounts of input data, knowledge and skills. The engineering models lack validation in order to be considered reliable and they have often to be shaped on the problem at hand; however, they seem to have the potential of producing a prediction model satisfying the above criteria. A review of the state of the art of these first three models for pile driving vibrations prediction is reported in [12]. Intelligent science models, which make use of AI techniques such as Artificial Neural Networks (ANNs) or support vector machine (SVM) learning theory, find instead wider application for the prediction of blasting vibrations [13].

A discussion on the modelling of vibration sources and wave propagation in the case of a theoretical model approach is presented in the following paragraphs with reference to a real case.

4 HISTORICAL HERITAGE IN A VIBRATION SENSITIVE AREA: THE ISOLA DEL GIGLIO CASE STUDY

D'Appolonia was involved in the pre-assessment and monitoring activities of the historical heritage at Isola del Giglio (Italy) during the operations for the Costa Concordia wreck removal. The development of the monitoring strategy followed the steps below:

- Survey and potential sensitive receptors identification;
- Measurements and photographic mapping before operations;
- Computational simulation of the vibrations propagation;
- 1st fast dynamic monitoring campaign (two days) with the aim of measuring the environmental noise (no operations) and the vibration level during the operations of seabed exploration;
- 2nd fast dynamic monitoring campaign (two days) with the aim of measuring the vibration level during the first seabed drilling activities;
- Calibration of the FE model according to the results of the two campaigns;
- Validation of the receptors choice and development of a long-term (end of operations and post-operations) SHM program proposal.

In the following, the attention will be focused only on those phases which preceded the long-term SHM program proposal.

4.1 Documentary and investigation phases

Given the heterogeneity and dispersion of the urban structure and the highly varying morphology of the coast, a survey was necessary to collect preliminary data on the site and the buildings but also to get an idea of the relationship in terms of scale and distance among the potential receptors. After the first survey, six buildings of historical and cultural interest were identified around the working site as potentially the most sensitive to the vibrations induced by the operations. A high-resolution photographic mapping of the buildings together with on-site measurements were done to collect reliable data on the state of the art of the buildings and their environment for subsequent FE modeling. Two images of the 3D model and of the mapping of one of the six historical buildings, the Church of Giglio Porto, are reported in Figure 1.

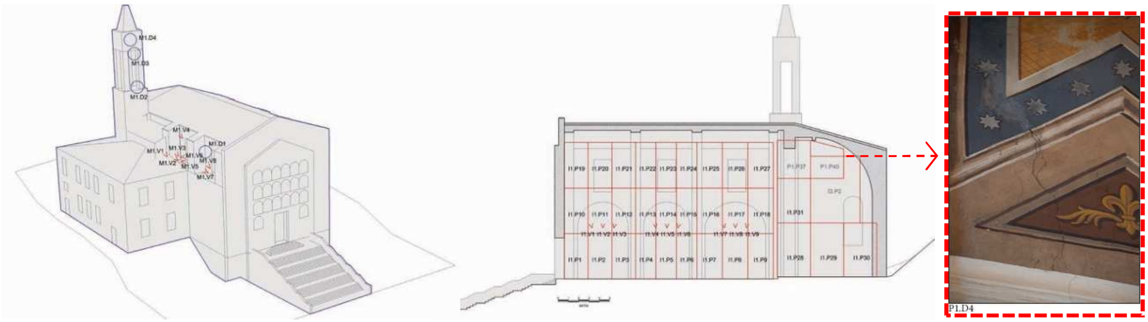

Figure 1 : 3D model and photographic mapping of the Church in Giglio Porto.

4.2 Support Phase

Once finished the surveying activities, a numerical model of the dynamic problem was set up in LS-DYNA [14] to describe the vibration phenomenon using explicit integration in the time domain. Simulations were used to guide the dynamic monitoring campaigns and, together with the results from the dynamic monitoring, to predict a geographical limit for the vibrations over a certain threshold (3 m/s^2 for historical heritage at foundation level according to Italian UNI9916:2014 [11]).

In order to make a realistic prediction, data of the soil layers, of the excitation source and of the site morphology had to be collected and integrated in the FE model.

4.2.1 Excitation sources

Two kind of excitation sources were considered: *drilling operations* and *blasting operations*.

Bored piles of different diameter were used on the building site and, consequently, it was necessary to develop several prediction models. For the present scope, only the technical specifications of the drilling operations which were active during the vibration monitoring are considered. Specifically, the considered bored pile data are a diameter of 146 mm, an axial pressure of 50 bar, a centrifugal force of 100 kN and a rotary speed of 500 rev/min.

For the blasting operations instead it was used a preparation of nitrocellulose (≈ 25%) homogeneously mixed with ammonium nitrate (≈ 75%) and contained in cartridges of variable size. The amount of explosives taken into account in the simulations is equal to 27 cartridges (60 g each). The total quantity of explosive cartridges was modeled as an equivalent mass of TNT adopting the proportion 1 kg real explosive = 0.61 kg TNT.

4.2.2 FE model

The FE model was developed using a plane-strain formulation and based on a series of 2D sections cut from a 3D model of the site morphology (Figure 2).

The soil stratigraphic analysis showed the presence of homogeneous rock material, gray granite, from the first meter of excavation. Qualitatively, the granite was found to have an average value of RQD > 80, with fractured plans angle which may vary, in principle, between 45° and 90°. The mechanical properties were instead derived from the results of uniaxial and triaxial tests (ρ = 2590 kg/m3, E = 32000 MPa, ν = 0.35 RQD = 80).

In order to avoid a strong over-sizing of the detected wave speed due to reflection effects at the boundary of the model, a Viscous Boundary Condition (VBC) was assigned to the boundary nodes of the model representing a limitation of the physical continuity of the material. Figures 2-3 show the development of the simulation from the site modeling to the analysis.

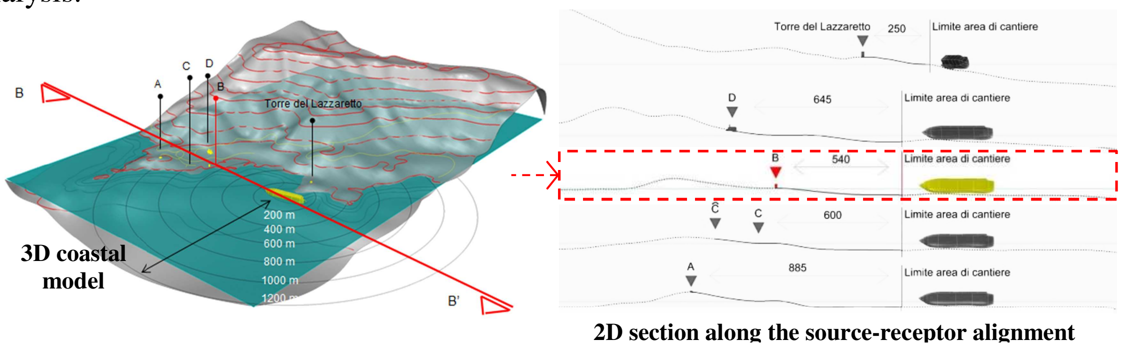

Figure 2 : Giglio Porto ground morphology reconstruction and analysis sections.

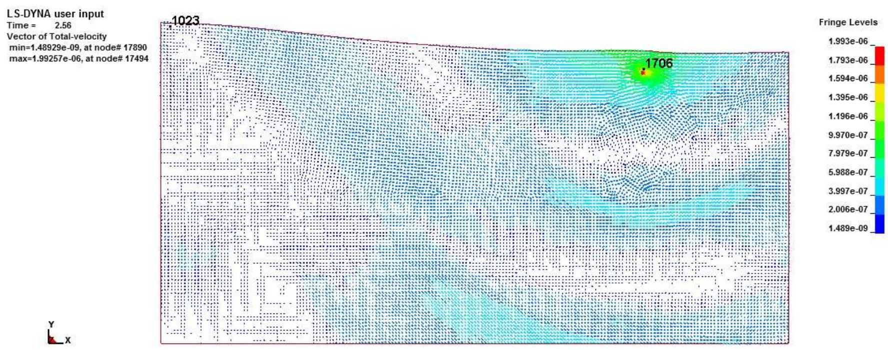

Figure 3 : Simulation of the underground vibrations propagation (drilling operations).

4.3 Scouting – selection –implementation cycle

Based on the surveys and on the simulation results, it was planned the topology of the sensor network for a two days campaign of dynamic monitoring (Figure 4).

The dynamic study of the ground near the Concordia working site was performed twice, with different boundary conditions, in order to:

- identify and define the properties of the vibration sources during the site works;
- determine the most probable propagation directions of the vibrations from its source;
- determine the intensity of the actions transmitted to the measuring points, as a preliminary indication of the possible effects, due to future similar site works/activities, on the buildings investigated;
- prepare the site map with the indication of the sensitive areas;

- identify the buildings that will be probably influenced by the vibrations;
- calibrate the computational FE model parameters.

Figure 4 : Monitored points (green triangles) around the working site.

The vibration measurements were conducted according to the Italian Standard UNI9916 [11], using a tri-axial geophone and ICP accelerometers assembled on stainless steel cubes in order to form bi- and tri-axial sensors.

4.4 Comparison of predicted and measured results

Measured values of the Peak Component Particle Velocity (PCPV) were finally compared to the results of the simulations (PPV - Peak Particle Velocity) and to standard limitations. Table 1 reports a summary of this comparison for the drilling operations considering the absolute maxima measured and predicted, independently of the drilling depth.

Table 1: Comparison of measured and predicted vibration levels of the drilling operations.

Distance from source [m]	Measured PCPV [mm/s]			Predicted PPV [mm/s]	Threshold value of PCPV (UNI 9916) [mm/s]
	X	Y	Z		
150	0.30	59×10^{-6}	41×10^{-6}	1.61×10^{-2}	2.5
300	60×10^{-6}	17×10^{-6}	14×10^{-6}	6.12×10^{-3}	

The values of PCPV resulting from both the measurements and the simulations are, for all scenarios, lower than the threshold values defined by the UNI 9916:2014.

Although the predicted PPV values, as expected, generally tend to overestimate the real vibration level, the measured PPV values at 150 m from the source have twice the magnitude of the predicted ones. The divergence of the predicted and measured values can be explained by looking at the several assumptions which necessarily had to be made, such as, for instance, the homogeneity of the ground layer. However, it is worth noting that, even if the assumed data were directed at obtaining conservative results, measurements show areas where the PPV was underestimated.

Another reason for the relative inconsistency can be found in other external excitation sources. If the vibration velocity had been higher than the threshold value defined by the standard, then a more accurate data processing would have been necessary to check the possibility of finding outliers among the measured peaks.

CONCLUSION

Monitoring of vibrations due to external sources, especially to construction activities, is a very important issue for the protection of architectural heritage buildings. The use of limitations indicated by international standards is a valid reference but several uncertainties should be considered when applied to building types different from to ones considered in setting the limits.

Careful design of the monitoring system is essential to obtain significant data but data interpretation is not always straightforward and the use of numerical models simulating the vibration sources, wave transmission through ground and the dynamic response of the buildings can help interpretation of the relevant phenomena and damage potential.

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