Innovative Structural Monitoring as Tool of Preservation and Valorisation of Monumental Architectures: The Case of Neptune Temple in Paestum (Salerno, Southern Italy)

Petti Luigi, Barone Fabrizio, Domenico Greco, and Gabriel Zuchtriegel

Abstract The knowledge of the real conditions and their evolution over time is the basis for maintenance processes aimed at the protection and conservation of monumental architectures. In complex conditions, including zones prone, in example, to seismic or hydrogeological hazard, the knowledge of the static and dynamic behaviour of the structures can be achieved using vibration monitoring systems by means of innovative devices and real-time analysis procedures. Currently, the real limit of this methodology is the need to have distributed and modular monitoring systems, adaptable and optimized for the specific structure, with non-invasive sensors (materials, dimensions and weights) characterized by high bandwidths and sensitivities. The paper describes the innovative monitoring project of the Neptune Temple carried out by the Archaeological Park of Paestum and Velia (PAEVE) and by the University of Salerno (UNISA), based on high sensitivity large band sensors developed at UNISA for a large variety of applications of monitoring and control. The monitoring system is a distributed modular continuous data acquisition and storage system, designed to provide real-time information on the dynamic response of monumental architectures due both to natural and human-induced phenomena. It will lead to carry out a research framework aimed at a synergic centralization of the contribution of researchers on the analysis of complex aspects that describe monumental structures as support tool of management plans.

Keywords Structural monitoring · Monumental architecture · Maintenance management

P. Luigi (✉) · B. Fabrizio · D. Greco
University of Salerno, Via Giovanni Paolo II, 132 – 84084, Fisciano, Italy
e-mail: petti@unisa.it

G. Zuchtriegel
Archaeological Park of Paestum and Velia (PAEVE), Capaccio - Paestum Via Magna Grecia 919, Capaccio, Italy

G. M. El-Qady and C. Margottini (eds.), *Sustainable Conservation of UNESCO and Other Heritage Sites Through Proactive Geosciences*, Springer Geology,
https://doi.org/10.1007/978-3-031-13810-2_20

1 Introduction

The recent negative natural and human-induced events, i.e., include Typhoon in West Japan in 2018, Earthquakes in Central Mexico in 2017, Kumamoto in Japan, Central Italy and Myanmar in 2016, Nepal earthquake in 2015, UK floods in 2015, Balkan floods in 2014 (UNESCO 2018), highlight the relevance of the maintenance process management, which should be approached with a dynamic vision, especially by considering the climate change impacts as well (UNESCO 2017a, b). For this purpose, the knowledge of the goodness (artifacts, monuments, sites, etc.) behaviour evolution plays the main role in the assessment and decision process (Petti et al. 2018c; Baratta et al. 2019). Therefore, real time monitoring techniques are of fundamental importance to support the assessment process of the behaviour of the Cultural Heritage continuously over time, from structural point of view as well.

Furthermore, the recent technological progress in this discipline lead to develop excellent broadband high sensitivity mechanical sensors.

Recently, a wide experimental campaign was carried out on the Trajan arch in Benevento (Italy) (Petti et al. 2017a, b), whose results were applied to the design of an innovative monitoring network of the temple of Neptune in the Archaeological Park of Paestum and Velia (Italy) (Petti et al. 2018a, 2019a).

The monitoring system implemented for the Trajan arch is an application of a general adaptive assessment strategy, with the aim to get an in-deep knowledge of the monument construction details by means of non-destructive investigations. This knowledge was obtained with an optimized design and implementation of a continuous and distributed monitoring of all its important structural elements, in connection with a careful analysis based on an adaptive structural FEM (Finite Element Method) dynamic model of the Arch (Fig. 1). With this process, it was possible to assess both the dynamic and static behaviours of the arch by using anthropic (traffic) and natural (wind) noise, such as to provide reliable description and clarification of the existing damage pattern on its sculptures and structural elements.

This above-mentioned strategy required the implementation and optimization of a numerical finite element model (FEM) describing the dynamical behaviour of the Trajan Arch based on measurements obtained with an adaptive monitoring system (Barone et al. 2015/1) as described in the following Fig. 2.

In the case of the Neptune temple in Paestum, several on site and laboratory tests were carried out to design the best strategy to monitor the Temple by means of an advanced sensors network. The tests, part of a joint research among the University of Salerno (IT), the University of Kassel (D) (DFG Project, "Tendon System for Protecting Ancient Column Structures", *TeSSPACS*), the University of Roma "La Sapienza" (IT) and the Archaeological Park of Paestum and Velia (PAEVE), consider on site accelerometric and seismic measures, laboratory medium and small-scale tests on columns and blocks sub-structures (Obón Santacana et al. 2017; Petti et al. 2018b, 2019b).

With regard to the on-site monitoring investigations, the structure of the Temple and the soil conditions were mainly investigated respectively in the 2016 and 2019

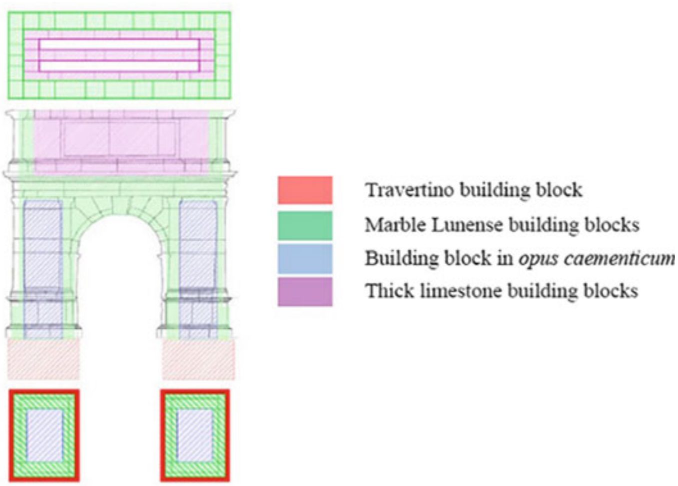

Fig. 1 Assessment of materials and construction details (Petti et al. 2017a, b)

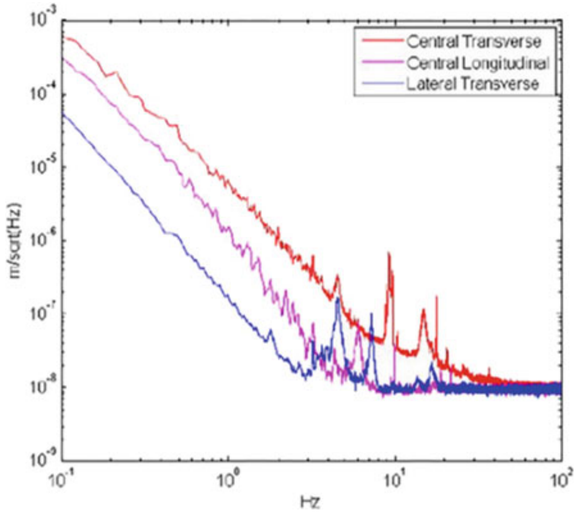

Fig. 2 Example of displacement spectral density of selected measurement points on the top of Trajan Arch (I test)

(Fig. 3), using triaxial accelerometric sensors, characterised by 0-200 Hz frequency range and 0.25 g maximum acceleration scale range.

Two test layouts were considered, and, in both cases, the accelerometers were installed on the north side of the Temple. In details, they were positioned between the fourth and fifth columns of the aforementioned side, numbering the columns from East to West. Figure 4 describes a test example.

The recorded signals analysis highlighted several peaks showing a complex dynamic behaviour due to the construction complexity.

Fig. 3 Monitoring campaign of Neptune temple, 2016

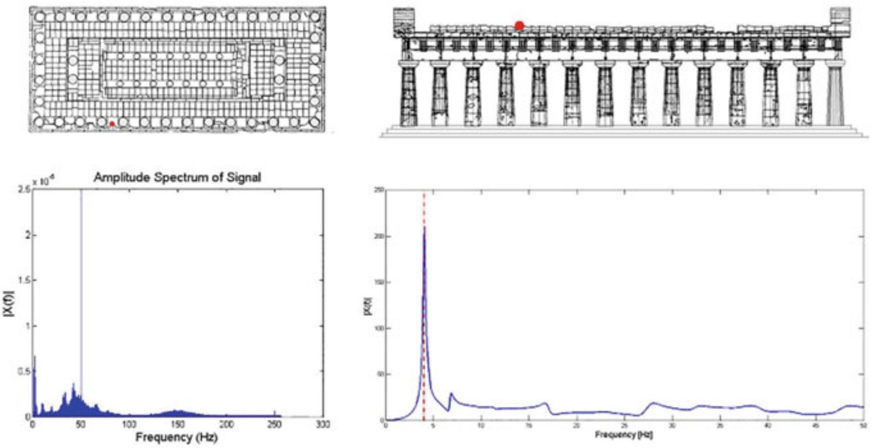

Fig. 4 Example of transversal accelerometric spectrum and Fourier transform in the frequency domain

Moreover, several tests (Petti et al., 2019a; Grelle et al. 2014) were carried out in the 2019 to assess the local seismic characteristics of the soil. In this context, indeed, it is fundamental to underline that the knowledge of a monument has to be based not only on the architectural and structural aspects but also on aspects concerning the structure-soil interactions.

For the Archaeological Park of Paestum and Velia, the particular conformation of the soil, geologically characterized by a complex process of evolution of the coast and the river branches, coming from the carbonate Apennine chains, strongly affect the local seismic demand.

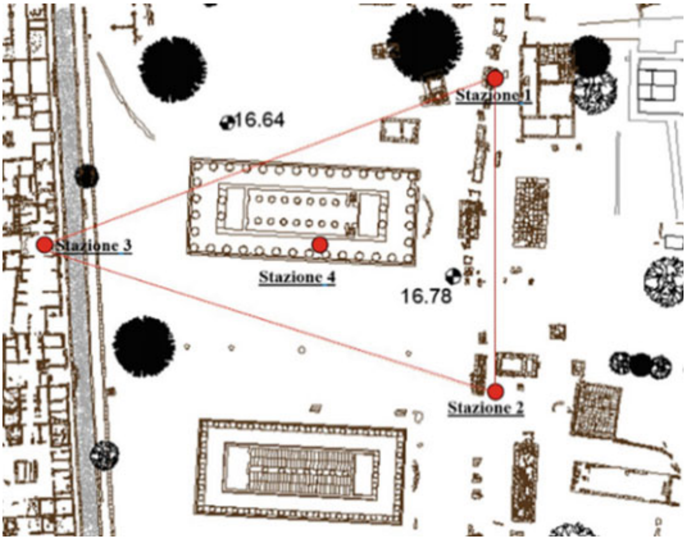

Fig. 5 On-site experimentation set-up, 2019

This seismic soil characterization highlighted a significant speed inversion of shear waves between the rigid superficial travertine bench, with an overall thickness exceeding 10 m, and the underlying loose deposited, presumably characterized by important pyroclastic fall and/or sedimentation contributions. This behaviour of the stratigraphy realizes a natural physical filter on wide frequency ranges, which presents most of the main natural modes of vibration of the structural elements and in particular in the frequency potentially damaging the temple.

Figures 5 and 6 describe the implemented seismic network and the main obtained results, respectively.

Moreover, the research activities carried out investigated the possibilities of using remote sensing technologies, as the satellite interferometric one (Bianchini et al. 2015; Casagli et al. 2017) that can be advantageous considered to assess long-time (weeks-years) global movements and deformations. These techniques allow to measure surface displacements of the ground or structures with millimetre precision thanks to the use of processing techniques called "interferometric", which consider the phase difference between SAR images (Synthetic Aperture Radar).

2 Neptune Temple Monitoring Network Framework

As part of the joint conservation activities between the Department of Civil Engineering (DICIV) of the University of Salerno and the Archaeological Park of Paestum

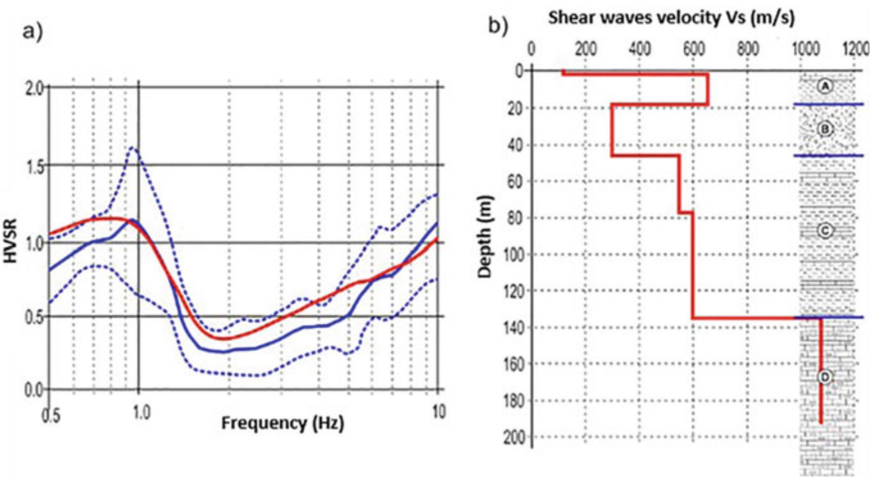

Fig. 6 On-site campaign: **a** result of inversion analysis between the experimental HVSR curve (blue) and the theoretical one (red); **b** speed profile of shear waves and relative stratigraphic column of reference: A = Travertine; B = River-Dunali deposits mixed with pyroclastic deposits; C = Compact or very thickened deposits of probable fluvial and marine origin; D = Basic Seismic Bedrock

and Velia (PAEVE), an agreement was stipulated in 2018, aimed at the direct monitoring and the analysis of the safety of the archaeological structures present in the Park, which envisages the realization of an executive project of a dynamic and seismic monitoring network of the Neptune temple. This network has as its main purpose the monitoring of displacements and accelerations induced by natural and human-induced events on the structure, in order to obtain a more in-depth knowledge of its behaviour, and also for the purpose of evaluating the safety of the monument and visitors. In details, modular biaxial and triaxial sensors, based on high sensitivity and large band and monolithic mechanical transducers (Acernese et al. 2010; Barone et al. 2015), are implemented.

As shown in Fig. 7, the 12 points indicated in the map of the Temple will be monitored. The data acquisition is fully locally distributed. An information structure (Totem), that will be installed near the Temple to show details to inform visitors about monitoring activities, to act also as a rack for the management of the equipment, data collection and storage, for an effective real-time pre-analysis and data transfer.

The passage of the monitoring network cables from the top of the Temple to its base is carried out by means of a cable-duct/sheath with a diameter of 7 cm along one of the columns of the West side of the Temple (Fig. 8).

More in details, the monitoring system of the Neptune temple in Paestum was conceived starting from the consideration that an effective evaluation and correlation of the static and dynamic structural behaviour of structures and sites, with natural and anthropic actions, requires the optimization and validation of adaptive structural finite elements models (FEM). Those models need a high quality and accurate experimental

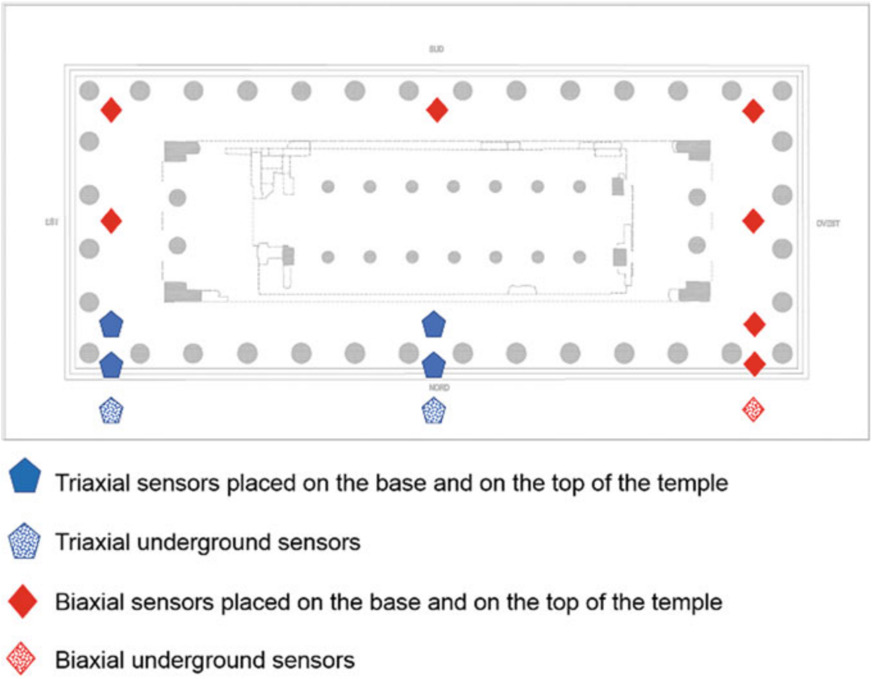

Fig. 7 Allocation of the mechanical sensors on the top, on the base and on the foundation layer of the Neptune temple

data, the latter acquired with modular distributed monitoring systems, adaptive both in terms of architecture and in terms of sensitivity and bandwidth of sensors. This innovative approach required a dual design action, aimed at both the implementation of the monitoring system and at the selection and specialization of sensors.

The monitoring system was designed to ensure not only compliance with the band and sensitivity requirements of the initial system for the different degrees of freedom (horizontal and vertical), but also with expandability and versatility (e.g., increase of the sensors number and/or repositioning), if the structural behaviour analysis requires actions aimed at the optimization of its performance. In order to optimize the signal-to-noise ratio, the acquisition will be obtained near the data production points (sensors), making, in this way, the system not sensitive to couplings with environmental noises. Figure 9 shows the block diagram of the data acquisition, storage, distribution and analysis system designed for the Neptune temple in Paestum.

The key element of the monitoring system is the local, compact and robust DAQ (Data Acquisition), based on the FieldDAQ™ technology of National Instruments, state of-the-art in the field both in terms of data quality and system robustness. The system consists of 34 degrees of freedom (sensors) acquired through 5 FieldDAQ™ voltage modules FD-11603 (8 voltage channels at ± 10 V, resolution up to 24 bits,

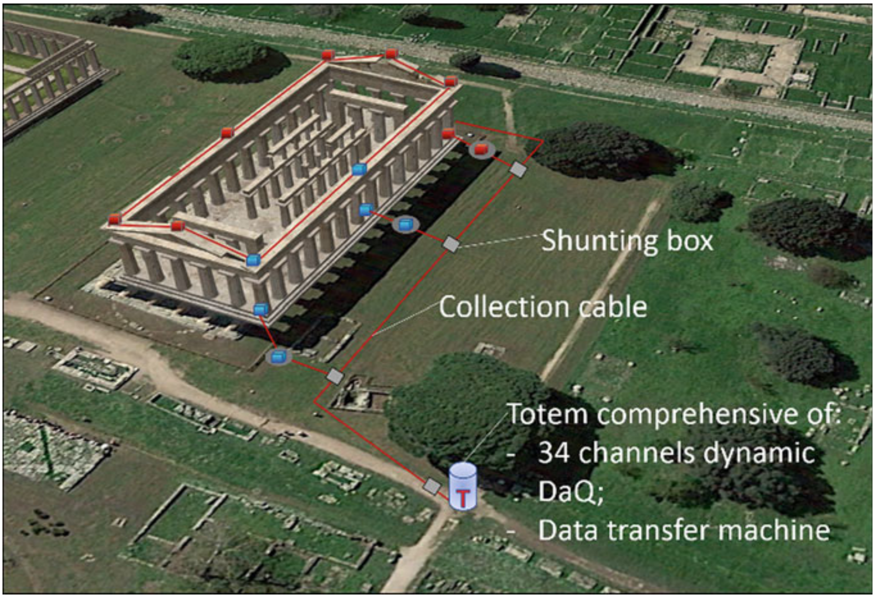

Fig. 8 3D view of the monitoring system set-up

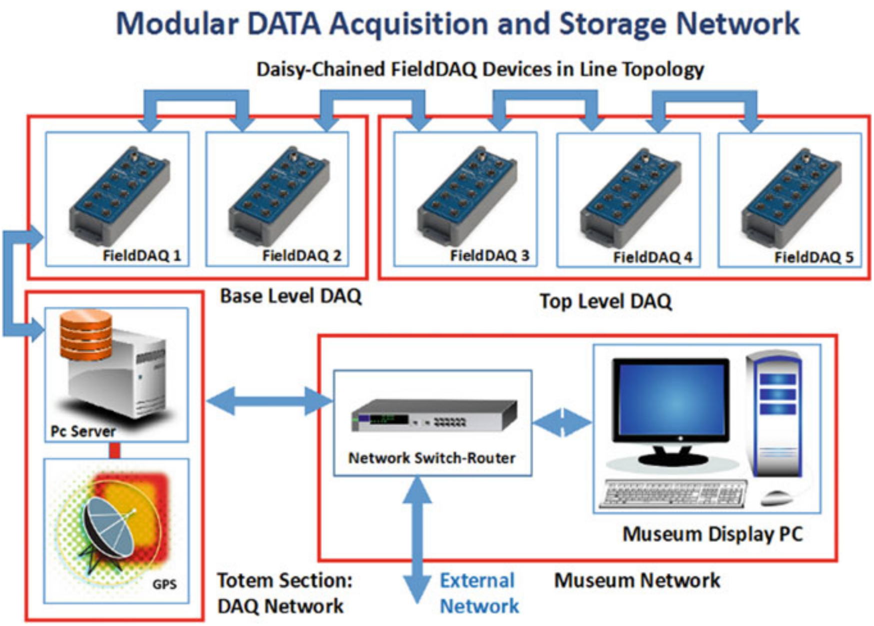

Fig. 9 Block scheme of the monitoring system of the Temple of Neptune in Paestum

simultaneous sampling frequency up to 100 kS/s, absolute accuracy of 0.019 V from −40 to 85 °C, less than 0.2% of the total measuring range).

In order to satisfy possible new requirements, the monitoring system can be easily expanded to the measurement of environmental conditions (temperature, pressure, humidity, wind speed and direction), relevant for the study of the dynamic slow-motion behaviour of the Neptune temple structure by cross-correlation analysis.

The data acquisition and storage processes are managed and synchronized by a Pc server (4 Tbyte) acting as frame builder and data storage system, downloading the data on local disks for backup, data distribution and presentation. The synchronization of the acquisition, better than 1 μs on the whole network of DAQ nodes, is carried out via Ethernet by the Pc server using the NI-DAQmx software. The time is provided by GPS card allowing, in this way, the definition of a timestamp on each frame, necessary for a correct reconstruction of signals.

The network topology, based on the IEEE 802.1AS profile (Ethernet TSN), is a daisy chain, chosen in consideration of the relatively low number of initial degrees of freedom (34) and of the relatively small distances among sensors. This network topology guarantees direct expansion of the number of sensors by increasing the number of DAQs, up to a maximum of 15 for a total of 120 channels. The simple addition of a TSN switch (compliant with the IEEE 802.1Q standard to support the Rapid Spanning Tree protocol (RSTP) and the IEEE 802.1AS standard to support synchronization of DAQs on individual branches) allows the extension of data acquisition and synchronization to other temples and structures of the historical area of Paestum, through the creation of a star configuration of daisy chains.

A direct connection to the museum Ethernet network is implemented mounting remotely the PC server storage disks through NFS, allowing both real time data backup and data presentation on monitors in museum rooms, using open software presentation standards (e.g., GEOPSY, typically used in seismology).

This technological approach leads possible also an easy development of dedicated presentation software, offering the visitor the opportunity to visualize via mobile apps in an effective and direct (even interactive) way the global and/or local dynamical behaviour of the temple of Neptune, also in connection with the daily evolution of the environmental conditions.

For what concerns sensors, the key element of the monitoring system, as it will be clear in the following, they have also been adapted to this specific application, which requires high sensitivity ($10^{-8} m/\sqrt{Hz}$) in the band ($1 mHz - 100 Hz$), together with small dimensions, weights and costs.

The design and implementation philosophy characterizing the data acquisition, storage, analysis and presentation system was extended to the sensors as well.

The mechanical architecture of the sensors is based on an innovative technological platform, developed by the Applied Physics Research Group of the University of Salerno (UNISA) Folded Pendulum, international state-of-the-art platform for the design and implementation of monolithic mechanical oscillators (Acernese et al. 2010; Barone et al. 2015).

This innovative technological platform, already protected by four families of international patents, has allowed the development of linear and angular (tiltmeter) position, speed and acceleration state-of-the-art sensors. These sensors, very innovative in the field of seismology, can be calibrated in frequency, are fully scalable in terms of sizes and weights with band in the low frequency region as large as $\left(10^{-7} - 10^{2}\text{Hz}\right)$, can be designed to guarantee very high sensitivities $\left(< 10^{-12} m/\sqrt{Hz}\right)$ in the band, (10 mHz – 100 Hz), even lower than the minimum seismic noise that can be measured on the earth's surface defined by the classical models (Peterson 1993; McNamara and Buland 2004). Moreover, they can operate in ultra-high vacuum (UHV) and cryogenic environments (<3 K), still remaining simple, compact, light and, with suitable designs, applicable to very different fields, including the cultural heritage one (Barone et al 2015; Barone and Giordano 2017).

The advantage of using a particularly sensitive and broadband instrumentation is that it allows a continuous evaluation of the dynamic behaviour of the structures, highlighting also effects of environmental forcing, such as those due to wind, to ground heating, to thermal expansion of the structures due to the different illumination from the sun during the day.

The sensors used in the initial monitoring network of the Neptune temple in Paestum, models SE-10H (horizontal) and SE-10 V (vertical) with a LVDT readout module, were slow motion seismometers (no feedback) in uniaxial configuration. These new sensors, produced by a privately owned company that develops sensors and systems for scientific and engineering applications for monitoring and control called ADV3S Company (Advanced Scientific Sensors and Systems, http://www.adv3s.com/en/homepage/*)*, are based on the model of an aluminium folded pendulum monolithic oscillator internationally known as GE15, a choice that guarantees the implementation of biaxial or triaxial configurations by means of suitable combinations of uniaxial sensors Fig. 10.

Being the GE15 mechanical oscillator limited by its thermal noise only, its sensitivity is practically determined by the readout system, that in this specific case is a commercial LVDT. Nevertheless, a LVDT readout upgrade with an optical readout allows to get a sensitivity improvement of three orders of magnitude $(< 10^{-11} m/\sqrt{Hz})$ and a band extension in the low frequency region.

Figure 10 shows the transfer function of the GE15 mechanical oscillator calibrated at the resonance frequency of 3.75 Hz, the different sensitivities in acceleration achievable with sensors based on GE15 monolithic oscillator according to the type of readout used and a picture of the basic architecture of the seismometers SE-10H and SE-10 V, based on the GE15 oscillator and on a commercial LVDT (Barone et al, 2015; Barone and Giordano 2017).

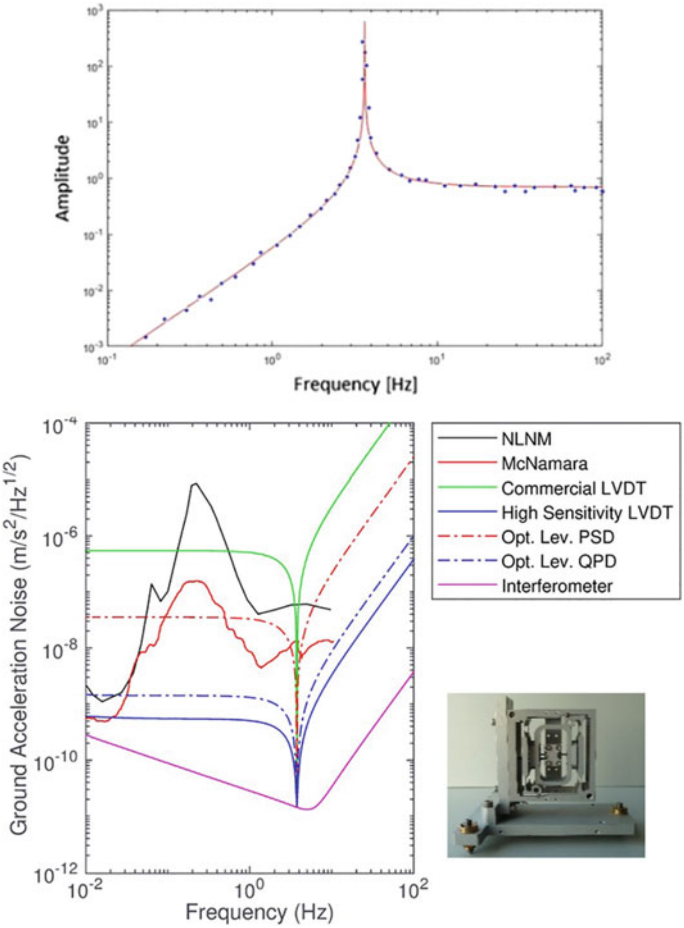

Fig. 10 GE15 mechanical oscillator transfer function calibrated at the frequency of 3.75 Hz (left); sensitivity (acceleration) of the GE15 monolithic oscillator equipped with different types of readouts, compared with the minimum levels of earth's seismic noise (Peterson (NLNM) and McNamara models) (right); GE15 sensor equipped commercial LVDT readout system (bottom right)

3 Conclusions

The paper presents an innovative network for monitoring the dynamic behaviour of the local seismic response of the Neptune temple in Paestum. The system uses an excellent broadband high sensitivity mechanical sensors network that allows to carry out an effective assessment of the static and dynamic behaviour of the temple structure, also in connection with the soil-structure interaction, also monitoring in real-time the effects due to human-induced and natural events, including, in example, those related to climate change phenomena. The network will allow a real-time data collection and storage, guaranteeing an effective dissemination of the information through open source platforms, key element for carrying out a research framework aimed at a synergic centralization of he contribution of researchers on the analysis of the complex aspects that describe monumental structures and for a share of further research activities.

Acknowledgements The research has been carried out with the support of Archeological Site of Paestum and Velia in Italy (Gabriel Zuchtriegel, Director; Antonella Manzo, Architect) and PRIN2015 National Research Project "Protecting the cultural heritage from water-soil interaction related threats" n. prot. 2015EAM9S5.

References

Acernese F, Giordano G, Romano R, De Rosa R, Barone F (2010) Tunable mechanical monolithic sensor with interferometric readout for low frequency seismic noise measurement. Nucl Instrum Meth A 617:457–458. https://doi.org/10.1016/j.nima.2009.10.112

Baratta I, Corbi O, Corbi L, De Andreis L, Marchetti L, Greco D, Petti L (2019) Heritage preservation: Challenges and perspective, STC 2019 International Conference. Salerno

Barone F, Giordano G, Acernese F, Romano R (2015) Watt's linkage based large band low frequency sensors for scientific applications. Nucl Instrum Meth A. https://doi.org/10.1016/j.nima.2015.11.015

Barone F, Giordano G (2017) The UNISA folded pendulum: a very versatile class of low frequency high sensitive sensors. Measurementhttps://doi.org/10.1016/j.measurement.2017.09.001

Bianchini S, Pratesi F, Nolesini T, Casagli N (2015). Building deformation assessment by means of persistent scatterer interferometry analysis on a landslide-affected area: the Volterra (Italy) case study. Remote Sens 7(4):4678–4701

Casagli N, Frodella W, Morelli S, Tofani V, Ciampalini A, Intrieri E, Raspini F, Rossi G, Tanteri L, Lu P (2017) Spaceborne, UAV and ground-based remote sensing techniques for landslide mapping, monitoring and early warning. Geoenvironmental Disasters 4(1):

Grelle G, Bonito L, Revellino P, Guerriero L, Guadagno FM (2014) A hybrid model for mapping simplified seismic response via a GIS-metamodel approach. Nat Hazards Earth Syst Sci 14(7):1703–1718

McNamara DE, Buland RP (2004) Ambient noise levels in the continental United States. Bull Seism Soc Am 94:1517–1527. https://doi.org/10.1785/012003001

Obón Santacana F, Dorka UE, Nguyen CKL, Petti L (2017) Behaviour of greek columns during earthquakes with and without tendon system, Lisbon

Peterson J (1993) Observations and modelling of background seismic noise, Report 93–322, U.S. Geological Survey, Albuquerque, New Mexico. https://doi.org/10.3133/ofr93322

Petti L, Sicignano F, Greco D (2018a) Valutazione della risposta dinamica e sismica del tempio di Nettuno: risultati preliminari. L'emblema dell'eternità. Edizioni ETS, Paestum. ISBN-13: 978–8846754639, pp 177–189

Petti L, Grelle G, Greco D (2019a) Procedure innovative pe l'analisi della risposta sismica delle costruzioni monumentali realizzate a blocchi rigidi. Il caso del tempio di Nettuno. Zuchtriegel, Carter, Oddo. Paestum. POSEIDONIA E L'ACQUA. Archeologia e cambiamenti climatici. ISBN: 978–88–87744–86–6, pp 123–133

Petti L, Sicignano F, Greco D (2017a) Dynamic behaviour assessment of ancient columns through experimental analysis. XVII Convegno ANIDIS, Pistoia

Petti L, Sicignano F, Greco D (2018b) Seismic and dynamic assessment of monumental structures made up of rigid clocks: the Neptune temple. In: 16th European Conference on Earthquake Engineering (ECEE), 18th -21st June 2018b. Thessaloniki

Petti L, Greco D, Mammone A, Di Muro C (2018c) New multi–scale risk governance and management approach of natural, cultural and artistical preserved areas. The case studies of the Amalfi coast and the Cilento National Park. 8th ICBR Lisbon

Petti L, Greco D, Nuccio F, (2019b). Seismic behaviour assessment of columns made up of rigid blocks. XVIII Convegno ANIDIS, 15–19 September 2019b. Ascoli Piceno

Petti L, Trillo C, Di Mauro M (2017b) Heritage and recostruction: Different perspectives. living under the threat of earthquakes, pp 101–116. ISBN: 978–3–319–68043–9. https://doi.org/10.1007/978-3-319-68044-6

UNESCO (2017a) Strategy for action on climate change, 39 C (2017a). UNESCO General Assembly, 39th session, Paris

UNESCO (2018) Proceedings of UNESCO chair program on cultural heritage and risk management. International Training Course on Disaster Risk Management of Cultural Heritage. Kyoto and Kobe, Japan, 29th August–19th September

UNESCO (2018) Proceedings of UNESCO chair program on cultural heritage and risk management. International Training Course on Disaster Risk Management of Cultural Heritage. Kyoto and Kobe, Japan, 29th August–19th September