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Cultural heritage structures and infrastructures vibration monitoring: vibration sensors metrological characteristics identification through finite elements modelling and simulation

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ABSTRACT
The preservation of historical structures and infrastructures requires a multidisciplinary approach, based on preventive and planned conservation actions. For such a purpose, digital technologies are increasingly used to adaptively model and verify the behavior and stability of heritage assets. However, the reliability of model outputs depends on the accuracy on input data, which, in turn, depends on an appropriate choice of sensors, based on their technical characteristics. This is why an accurate design of monitoring system is crucial. Considering the installation and operation costs for a tailored system, it would be better to understand in advance the expected dynamic response of the structure or infrastructure to fit the monitoring system characteristics to the monitored structure . This is why, this work applies the use of FEM-based simulations to provide preliminary indications on the expected dynamic behavior of a heritage asset, supporting the identification of metrological parameters, in terms of sensors positioning and signals expected features. The used FEM, referred to a prototype of a Doric column, being the scaled 1:5 copy of a marble colonnade of the Temple of Apollo at Bassae (Greece), was designed, reproducing the parameterization (i.e., shape, measures, materials, etc.) of a previous FEM model, implemented and validated on the basis of experimental tests performed at the National Technical University of Athens. The results shed light on optimal sensor positioning and expected signal amplitudes, demonstrating the model's effectiveness in crafting tailored monitoring solutions for preventive conservation. The study underscores the importance of integrating Finite Element Modeling (FEM), avoiding the usual initial parallelization of model design and its experimental validation, into the creation of 'phygital' systems, that blend physical monitoring with digital twins. This approach not only enhances the accuracy of conservation efforts, but also suggests a promising direction for future research aimed at applying this methodology across a diverse range of heritage structures to support proactive preservation strategies.

Section: RESEARCH PAPER

Keywords: vibration; applied physics; cultural heritage; Greek temple; Finite Element Model; phygital system; measurement

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1. INTRODUCTION

The need of preserving cultural heritage structures and infrastructures requires to be addressed through a multi-disciplinary approach, whose relevance is acknowledged in the fields of archaeology and cultural heritage studies [1], [2]. In fact, considering the multiplicity of technical requirements and norms involved in the management of these immovable assets, only a multi-disciplinary approach can guarantee the necessary competency for their appropriate preservation and valorization.

With the same purpose of preserving cultural heritage structures and infrastructures, cultural heritage managers gradually became aware about the relevance of preventive and planned conservation. This awareness is reflected in the evolution of European and international regulations, since the successful preservation of heritage structures and infrastructures critically depends on their frequent care and maintenance [3]. However, considering the huge number of assets to protect, in order to plan their maintenance, protection and restoration, actions need to be supported by the application of innovative monitoring instruments, methods and procedures, that can support informed decision-making processes. In fact, an up-to-date knowledge of the dynamic conditions of the assets, that need to be preserved due to their historical and cultural relevance, is of paramount importance.

The availability of digital technologies and tools allowed to implement the applications of digital twins, consisting in evolving adaptive models of real objects, that are designed on the basis of the available structural, chemical and physical properties data, eventually integrated with data, collected either from separated or from integrated monitoring systems, which are installed and operated to provide an input to the model, being able to evolve along time, eventually supporting the provision of forecasts on the structural health of the monitored asset. In the case of structures and infrastructures of historical, archaeological and cultural relevance, digital twins are considered a promising option to improve the management of complex engineered systems, that are widely diffused, and, so, difficult to manage [4]. In fact, their applications for cultural heritage can support informed decision-making processes and the preventive maintenance of heritage assets, while increasing a structured and accurate collection and storage of documentation about the modelled asset [5].

Despite the utility of digital twins, enabling the combination of information and communication technologies and appropriate algorithms with field data [6], their reliability depends on the quality of input data, which should include a detailed knowledge on the structural design, the materials, an accurate parameterization, as well as on a correct implementation of the interface between the asset monitoring system and its digital counterpart [7], [8]. This is why, especially in the case of heritage structures and infrastructures, the approach to adopt is a mutual and synergic optimization of both the model and the monitoring system. This optimization, in turn, should start from the very beginning, avoiding to parallelize the construction of a dynamic structural model (e.g., a Finite Element Model) and its validation, supported by the installation and operation of a vibration monitoring system.

While considering the integration between digital models and monitoring systems for the preservation and protection of heritage structures and infrastructures, the implementation of digital twins should rely on an appropriate choice of sensors, based on their technical features and on their possibility of being integrated into a coherent system, in order to provide sufficiently accurate data to implement the digital model [9]–[11]. On the other side, however, with respect to monitoring systems, there are also installation and operational constraints, including the risk of damage for the heritage asset, a limited budgetary availability with respect to the potential cost of advanced sensors and systems, as well as the need of remotely managing a distributed monitoring system. This is why the sensors key technical metrological characteristics should be accurately chosen during the design of the integrated digital and physical (i.e., monitoring) system, together constituting a so-called ‘phygital’ system [12], being the integration of physical sensors and digital counterpart, adaptively interacting with its physical counterpart to produce a certain output (e.g., structural health parameters; indications about potential actions, that need to be performed by specific individuals, etc.), that, in the context of heritage structures monitoring, could serve to manage their structural health, supporting the early identification of potential stability risks, that could significantly damage the monitored structure. With this respect, the use of modelling and simulation, following a preliminary field survey and data collection, can support this choice. In particular, a Finite Element Model (FEM) can support this process.

In assessing the structural integrity, particularly through vibration analysis, the employment of Finite Element Models (FEMs) is a standard approach. These models, facilitated by a variety of digital platforms and proprietary software, play a pivotal role in both the conceptualization and dynamic visualization of intricate architectural entities and their components. Specifically, within the domain of cultural heritage preservation, FEMs serve a critical function in deducing the structural stability, informed by data derived from empirical observations, collected during onsite evaluations or through examinations of their scale models in a controlled laboratory setting [13], [14]. In the same disciplinary context, FEMs are also integrated to support seismological [15], [16] and structural models [17], [18]. Usually, considering the interoperability of FEM outcomes, that can be integrated with Building Information Modeling (BIM) design software, FEMs are used to support planning actions, as well as structural stability analyses. This study specifically aims to assess the efficacy of FEMs in optimizing vibration monitoring systems, identifying the potential best positions for sensor placement and the expected signal amplitude.

Overcoming the parallel design of FEM and choice, installation and operation of the monitoring system, used to validate the FEM simulations outcome, this research seeks to bridge this gap, providing a better and coherent approach for an adaptive integration of monitoring solutions and digital twins, starting from the first phase of the mutual optimization process. Introducing the possibility to use FEMs to infer what could be the expected vibration signal outcomes, it would be possible to define the desired sensors technical features in relation to the expected structural response, guiding researchers and practitioners in the search for more tailored instrumental solutions, instead than defining the choice of sensors on the basis of their availability or potential apparent advantages (e.g., easier data transmission; lower cost; easier to handle by non-experts).

The relevance of this procedural option depends on its potentiality in contributing to the reduction of monitoring systems installation and operation costs, through a FEM-aided design of the preliminary monitoring system configuration requirements. The data, derived from installed monitoring system, in turn, could be used not only to validate the FEM and to match the FEM data with the experimental measures, but also to adaptively integrate the monitoring system and the digital model, optimizing the choice of sensors and their positioning, as well as the functioning of an integrated management system, composed by the monitoring system and the digital model counterpart. The obtained adaptive system, then, could be especially useful for a long-term monitoring of heritage structures.

Consequently, this work proposes to use the FEM as a tool to produce a first guess on the configuration and technical requirements for a vibration monitoring system. In order to rely on the most affordable results available in the literature, we reproduced a FEM, validated through experimental measures and supported by a complete sensitivity analysis, in the context of an international project, whose results were already available in the literature. In particular, we reproduced, through a FEM, the 1:5 scaled model of a basic colonnade, made of two multi-drum marble columns and an epistyle, reproducing part of the temple of Apollo at Bassae (Greece). The complete structural and experimental validation data were kindly provided by the NTUA research group, that performed the original collection of field data, built the scaled version of the colonnade and performed the experimental measures. On this basis, then, we define the initial requirements in terms of sensors characteristics and expected better positioning on the structure.

As evident, this work does not aim to improve the approach to FEMs, with their inherent challenges, such as the rigorous validation of the model against empirical data, computational demands, and uncertainties inherent in the input data, particularly in the context of structures with complex historical backgrounds. Model validation must be approached meticulously, recognizing that the parameters used are often derived from a combination of historical records, empirical testing, and assumptions that may not fully capture the unique nuances of heritage structures. Computational complexity also presents a hurdle, necessitating substantial processing power and advanced algorithms to accurately simulate the physical behaviors of intricate architectural elements. Furthermore, the uncertainties in input data, such as variations in material properties over time and incomplete historical records, introduce an element of indeterminacy that must be carefully managed to ensure the robustness of simulation outcomes. Nonetheless, in the proposed study, the discussed use of FEM as a tool to produce a first guess in the design of a monitoring system would be the first step of a mutual adaptive process, involving the optimization of the monitoring system and the model, that can go beyond the definition of a correct structural parameterization in the model, as usually done for FEMs, producing evolutive analyses of the heritage asset structural behaviour.

Section 2 will introduce the selected case study and the methods, including the numerical model features and parameters, and the basic simulation procedure outline. Then, Section 3 will provide the implemented FEM outcomes. Section 4 will discuss the validity and limitation of the obtained results and how these results could be integrated into an adaptive phygital (physical and digital) system representing the dynamic behaviour of the considered structure or infrastructure. Finally, in the concluding section (i.e., Section 5), the key results are summarized, together with the potential impacts of the obtained results.

2. CASE STUDY AND METHODS

2.1. Case study

The developed FEM leverages prior understanding of the structural geometry and material characteristics, with its simulation results being validated by experimental data, obtained from the Soil Mechanics Laboratory at the NTUA [19]–[22]. The FEM crafted a 1:5 scale segment of a colonnade from the Temple of Apollo at Bassae (Arkadia, Western Peloponnese, Greece), constructed in the 5th century BC. This temple, part of a UNESCO-recognized site, stands as one of the initial monuments postdating the Parthenon where the trio of ancient Greek architectural orders -— Doric, Ionic, and Corinthian — are integrated. The structural simulations, along with their laboratory counterpart supported by onsite data collections were predominantly conducted under the European Commission funded project "Performance-based approach to the earthquake protection of cultural heritage in European and Mediterranean countries" (PERPETUATE).

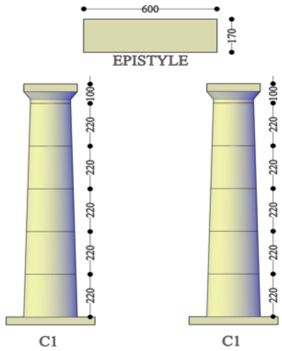


Figure 1. Colonnade unit measures, with measures expressed in units of cm. The equal code (C1) attributed to both columns indicates that their parameterization is equal. Measures are given in mm.

The artifact, for which the National Technical University of Athens (NTUA) researchers provided geometric specifications, material composition details, and experimental data, was subjected to modelling. The resulting FEM consisted of two identical multi-drum columns surmounted by an epistyle. The system's geometric characteristics are delineated in Figure 1.

In alignment with the original laboratory and digital representations, the columns and epistyle were constructed from identical materials, facilitating accurate modelling of the interactions between the epistyle and the capitals of both columns, as well as between the individual drums. The dimensions of the physical model, which replicates the real marble colonnade from the Apollo temple at Bassae (Greece), were adjusted to a 1:5 scale. This scaling was applied to all physical parameters in accordance with the scale factor, as documented in existing literature [20] and detailed in a generalized form, for a 1:N model, in Table 1.

In the proposed simulation, the model neglected the soil-structure interaction, in order to reproduce the results of the validated FEM. Even though the soil-structure interaction is particularly of concern in the context of significant seismic actions, that can induce rocking motions of the drums or sections, given the low intensity of the applied horizontal actions

Table 1. Dimensional relations between full scale object and laboratory model with 1:N scale (source: [20])

Variable	Real object/Scaled model
Length	N
Area	N^2
Volume	N^3
Mass	N^3
Density	1
Strain	1
Stress	N
Young's modulus	N
Time	$N^{0.5}$
Frequency	$N^{-0.5}$
Acceleration	1
Force	N^3
Moment	N^4

and the specific purpose of the current study, that is not related to a detailed structural modelling of the colonnade, but focuses on the use of FEM as first-guess tool for defining the expected technical and installation requirements of a vibration monitoring system, the inclusion of soil-structure interaction was deemed not crucial for the scope of this research. Nonetheless, it must be remarked that, having in mind the purpose of an adaptive integration and optimization of the monitoring system and the model, these modelling improvements should be incorporated in the next optimization steps. The scope of dynamic simulations in this study was confined to ground motion (acceleration) along the axis parallel to the epistyle, mirroring the approach of NTUA researchers. This constraint was essential to ensure comparability between the FEM and empirical laboratory data throughout the model's configuration process.

2.2. FEM parameterization

The FEM was implemented and the simulation was performed using ABAQUS commercial software, produced and sold by SIMULIA™ [23]. The model considered a scaled basic colonnade, constituted by two multi-drum columns and an epistyle, whose geometric properties are detailed in Figure 1. Solid brick elements, having a maximum dimension of 30 mm, were used to model the colonnade elements.

In agreement with the NTUA experimental tests and simulations, the density used for marble was 2400 kg/m^3, with elastic modulus of 35 GPa and Poisson ratio equal to 0.2. All the parameters, including the inter-drums tangential interface parameters, were modelled according to the experimental results [22], [24], [25]. Validated model parameters included also the friction coefficient equal to 0.7.

The interaction between drum segments was simulated using a "hard contact" finite sliding model, setting the penalty to match the coefficient of friction. Materials were assumed to behave as linearly elastic. To maintain the conservativeness of outcomes, material damping was omitted, aligning with methodologies adopted in a prior publication [26]. Consistent with the referenced study, the present investigation omits the impact of damping on peak displacement outcomes. The anticipated nonlinear responses in the simulations are solely attributed to geometric factors and the occurrence of significant displacements. However, in the next steps of the optimization processes, it should be acknowledged that the model would face limitations, due to the extreme heterogeneity of materials used in historical structures and the challenges in accurately modelling the contact between stones and interface degradation over time.

2.3. Simulation input and output

The analysis was conducted using two consequential steps, which can be found in the “step” menu of ABAQUS. The first one is used to apply the gravity load (GL) though a “static, general” analysis. The second step is used to apply the input signal, using a “dynamic, implicit” analysis and accounting also for the geometric non linearities (“Nlgeom” command in ABAQUS). In particular, considering that the krepidoma (the foundation beneath the column) and the columns were constructed from identical materials, an acceleration signal simulating ground motion was applied at the base of the colonnade utilizing a dynamic implicit analysis. Effects of the second order were integrated directly within the procedural steps of the analysis.

Two different input signals were used to assess the structural response. First, a time-domain Ricker wavelet, as a possible form

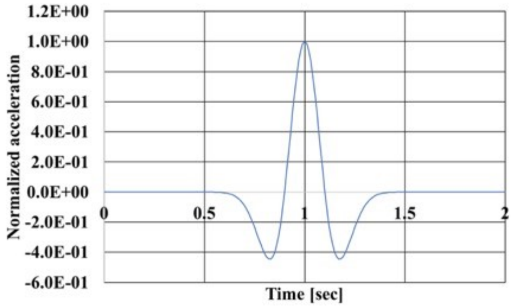


Figure 2. Synthetic seismogram signal (Ricker wavelet) applied as simulation input signal.

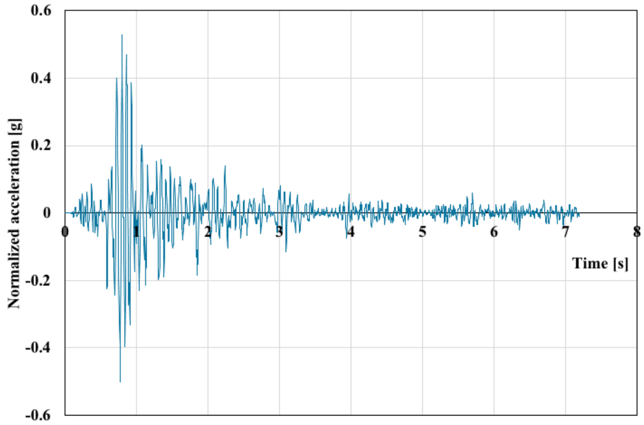


Figure 3. Normalized acceleration (in units of g) time sequence for the Athens earthquake, occurred on Dec 24, 2017, as recorded by ITSAK Strong Motion Network at the site - station code ATH3 applied as simulation input signal.

of a synthetic seismogram, was applied [27]. The representation of the signal in time domain is given in Figure 2. Its maximum frequency is 2.24 Hz (indicated as 4p in a previous literature work [24]). This signal, having a maximum acceleration amplitude of 0.6 g was also applied to verify the match between the simulated data and the data provided by NTUA, confirming the expected match.

Subsequently, the longitudinal (LT) component from an actual earthquake signal was introduced. The earthquake signal in question (identified by station code ATH3), for which data was sourced from the European Plate Observing System (EPOS) Engineering Strong Motion (ESM) Database, originated in Athens, Greece, on December 24, 2017. It featured a peak ground acceleration (PGA) of 0.263 g and lasted for 40.77 seconds. A graphical representation of the time sequence for this selected earthquake signal is presented in Figure 3.

2.4. Application of virtual sensors and simulation-based indicators

A set of virtual displacement and acceleration sensors were placed at each inter-drum level, between the upper drum and the capital at the capital-epistyle interface [28], [29]. The position of each virtual, indicated in Figure 4, is identified through a capital letter (D) and a number (from 1 to 12).

Given that, at the simulation's outset, the drums within each column are positioned in alignment along their respective axes, equidistant to the span of the epistyle, the change in the inter-axial spacing of each drum pair from the two columns can be tracked. Pairs of virtual sensors were deployed at identical elevations on both columns. Specifically, referring to Figure 4, sensor pairings are established as D1 with D7, D2 with D8, D3 with D9, D4 with D10, D5 with D11, and D6 with D12.

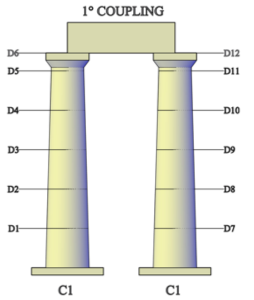


Figure 4. Position of the virtual sensors in the digital model, identified with the capital letter D, followed by a number (right part of each figure).

After running each simulation, relative displacement and acceleration data were extracted for each virtual sensor. Then, in order to assess the inter-axial relative displacement variability with respect to its initial value, based on each sensor couple, the normalized index of inter-axial relative variability (NIRV) was calculated:

$$NIRV = \frac{D_\mathrm{a} + EL + D_\mathrm{b}}{EL}\,, \qquad (1)$$

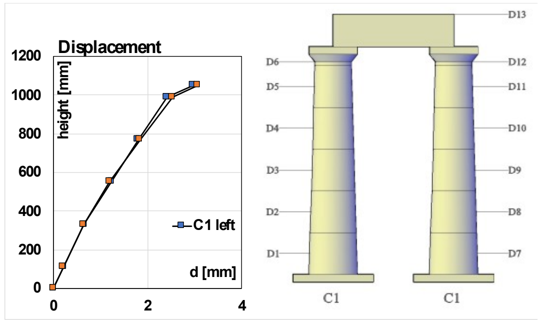
where $NIRV$ is the normalized inter-axial distance value, D_a and D_b are the relative displacements for each column, as calculated for each virtual sensor couple, at a certain time. Finally, EL is the epistyle length, being equal to the initial inter-axial distance between the two columns. This parameter, obviously, is meaningful in the context of modelling a colonnade unit or its extension to larger colonnades, considering that the variation of column interaxial distance would impact on the stability of the epistyle.

2.5. Frequency response analysis

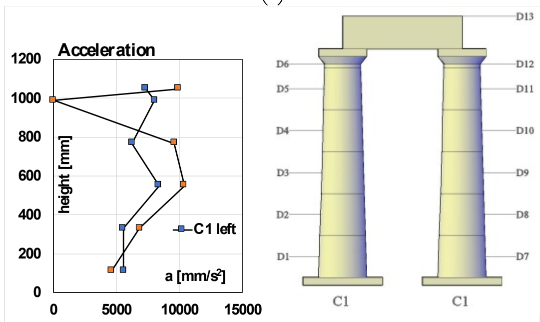
The most relevant natural frequencies of the colonnade were calculated, in order to retrieve the expected structural frequency response. In particular, a "frequency" analysis, that is found in the ABAQUS "step" menu, was performed using Lanczos eigensolver, fixing the number of eigenvalues to 8. The initial stress effect due to preloads and initial conditions were accounted for as boundary conditions. Instead, the stiffness effects were excluded from the initial condition set-up, since the geometric nonlinearity was excluded from the analysis procedure.

Based on the fact that obtained values refer to the scaled column model, expected frequency values for the real structure need to be scaled according to the values defined in Table 1. The identified natural frequencies do not constitute an indication for limiting the instrumental frequency range. Instead, they indicate why, at certain signal frequencies, we might detect signals with a wider dynamic range, due to the natural resonance phenomena, that are expected, depending on the quality of survey data and modelling procedure, at those frequencies.

In order to assess the variability of natural frequencies depending on little parameterization changes associated to different materials, travertine was selected as alternative to marble, considering that this type of stone was used in some cases, like the Greek temples in Paestum (S Italy) [30], [31]. With this respect, mean parameters referred to Italian travertine, derived from previous literature studies, were used [32]. In particular, the travertine density used in the model was 2140 kg/m^3, the elastic 38.8 GPa and the Poisson ratio equal to 0.2.



(a)



(b)

Figure 5. Maximum relative signal amplitude, based on the Athens earthquake signal as input. (a) Displacement signal; (b) Acceleration signal. On the left, the maximum displacement or acceleration signals are plotted for different reference heights. The blue colour refers to the left column, while the red colour refers to the column on the right.

3. RESULTS

3.1. Maximum expected displacement and acceleration

The displacement and acceleration data, extracted for each virtual sensor, were analysed to define the expected signal amplitude dynamic range. Positions, where a higher displacement or acceleration could be detected, were identified accordingly. On this basis, sensors with different amplitude dynamic range might be chosen.

Maximum relative displacement and amplitude at different levels are displayed in Figure 5a and Figure 5b. From the case study, which yielded results analogous to those obtained by NTUA, an increased relative displacement of the right column compared to the left one was observed. Additionally, the right column exhibited greater displacement than the left, with the capital being the exception, possibly due to the epistyle's role as a mechanical connector between the two columns. Conversely, the peak acceleration was noted in the second column at 660 mm, aligning with the upper segment of the third drum.

Considering that obtained values refer to the scaled column model, as defined in Table 1, expected displacement and acceleration values should be scaled according to their conversion factor (5, considering this case study, based on a 1:5 scaled model, for the displacement signal; 1, in the case of acceleration).

Consequently, expected relative displacements, in the case of the selected earthquake for the real colonnade, might reach the order of 10^{-1} m, while the computed maximum acceleration was between 3 and 4 m/s^2. These values are given here as exemplification of the complete procedure, to evaluate the expected dynamic amplitude range for the displacement or acceleration signal. Obviously, this analysis should be contextualized with respect to the place where the structure or

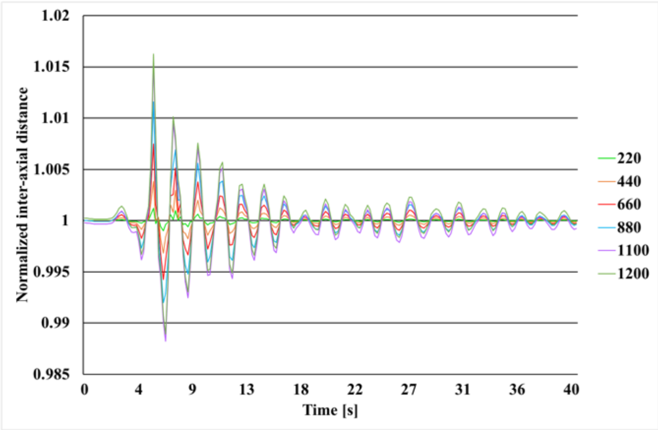


Figure 6. Values of normalized inter-column displacement variability index (i.e., the normalized relative displacement index called NIRV), derived from the virtual sensors data at different heights, as identified by the legend (heigh in millimetres).

infrastructure is found. Differences between expected and observed signals will occur, depending on the Soil-Structure interaction being characteristic of the site, on the natural and anthropogenic seismic signals, which can be recorded at the foundation level, as well as on other environmental factors, such as solar radiation or wind or atmospheric precipitations, that could affect the dynamic behaviour of the structure, depending on the interaction between these environmental phenomena and the monitored structure. Thus, in similar contexts, it would be always better to opt for a multi-parametric monitoring system.

3.2. Inter-axial distance variability characterization and system optimization

Analysing the extracted data, the values of NIRV at different levels are calculated. Higher values of NIRV correspond to a higher inter-column displacement or acceleration variability, on which the choice of different instrumental sensitivities might be based. Consequently, for a colonnade, higher NIRV values imply also a higher risk of structural instability. Thus, the number of sensors could be reduced, choosing the places with higher NIRV values as preferential initial installation points. These points, obviously, will require, then, to be re-evaluated and optimized on the basis of real field conditions.

Figure 6 shows the NIRV time variation, based on the Athens earthquake signal represented in Figure 3. The obtained data indicate a coherent variation for the inter-axial relative distance during the earthquake event. An exception is represented by the virtual sensors (D5 and D11) positioned at the contact point between the epistyle and the capitals, confirming the mechanical action of the epistyle, operating as a link.

Based on the findings, it is possible to observe that the constructed multi-drum columns, integrated by the epistyle into a singular unit of a colonnade, manifest varying relative displacements and accelerations. These values are consistent at the foundation and at the capital-epistyle interface. Additionally, a more pronounced relative displacement is observed between the uppermost drum and the capitals of both columns, notably on the column to the right. In contrast, the most significant variation in acceleration is discernible at lower inter-drum connection levels.

Within the specified seismic event, the colonnade behaves as a unified entity, apart from the junction between the epistyle and the capitals, where the relative inter-axial distance exhibits less fluctuation over time. This evidence might allow to reduce the number of sensors, removing the sensors displaying a lower signal amplitude variability. In particular, considering the integration of information derived from Figure 5, moving along the vertical axes, sensors from D3 to D6 and from D9 to D12, with the exception of sensors D5 and D11, should be kept, if possible, depending on the installation and operational costs. On the contrary, at least the two couples of sensors D2 and D8 could be removed. Conversely, D1 and D7 sensors could be moved to the basement to monitor the input signals.

3.3. Expected structural frequency response

The first eight expected natural frequencies (or periods) of the real-scale and scaled marble colonnade, reproducing the case of the Apollo temple at Bassae, are detailed in Table 2.

The first 8 calculated natural frequencies for the marble colonnade have a value of 25.05 Hz, 37.03 Hz, 66.55 Hz, 135.26 Hz, 144.95 Hz, 187.96 Hz, 195.31 Hz and 273.91 Hz.

Modifying the stone material and substituting the properties of marble with those of Italian travertine, the results showed that the natural frequencies of travertine colonnade (Table 3) displayed a variability around 10% with respect to the marble colonnade. However, this frequency response should not constitute an indication for limiting the frequency range of the structure.

In fact, the quality of initial simulations depend on the quality of field survey data, which might be even less accurate, in the case of a more complex structure or infrastructure (e.g., building, theatre, temple, etc.). Instead, broadband sensors should be preferred in any case, as confirmed also by past experiences, as the monitoring of the Trajan arch in Benevento (S Italy) or the Neptune temple in Paestum (S Italy), where lower frequencies were detected by instrumental records, depending on different natural and anthropogenic forcing, as well as on the variability of materials [33], [34].

Table 2. Real scale and scaled (1:5) marble colonnade natural frequencies, expressed in unit of Hz, and periods, expressed in units of s.

	Scaled model colonnade	Real scale colonnade
	Frequency in Hz	Frequency in Hz
1	56.01	25.05
2	82.82	37.04
3	148.82	66.55
4	302.45	135.26
5	324.13	144.95
6	420.30	187.96
7	436.74	195.32
8	612.48	273.91

Table 3. Real scale and scaled (1:5) travertine colonnade natural frequencies, expressed in unit of Hz, and periods, expressed in units of s

	Scaled model colonnade	Real scale colonnade
	Frequency in Hz	Frequency in Hz
1	62.45	27.93
2	92.34	41.30
3	165.94	74.21
4	337.24	150.82
5	361.41	161.63
6	468.64	209.58
7	486.97	217.78
8	692.92	309.88

4. DISCUSSION

The simulation results allowed to identify the variability and maximum amplitude of displacement and acceleration data, as possible variables used in assessing the dynamic behaviour and stability of a historical structure or infrastructure. Starting from the validated model-scale colonnade, it was possible to derive the magnitude of expected displacements and acceleration in case of an artificial seismogram, as well as of a real earthquake signal, as recorded from a monitoring station.

The possibility of integrating the use of historical earthquake records and artificial seismograms, as input signals, allowed to derive the expected signal amplitude at different heights for the modelled colonnade. This information, in turn, could be used to select a more suitable vibration sensor, based on its sensitivity and amplitude dynamic range, for monitoring the modelled structure.

Despite the results obtained with the assessment of the natural frequencies, whose variability depends on how different construction materials and other structural parameters are modelled, the use of broadband sensors, covering a wide range of frequencies would be more desirable, considering the wide range of natural and anthropogenic inputs [35]–[37], that could impact on the structure.

Using the interaxial relative displacement variability as a relevant geometric parameter for a colonnade, it is possible to assess, for different positions, the relative displacement and acceleration with respect to the reference position of the columns (i.e., their vertical axis). The identification of positions with higher relative displacements or accelerations allows to potentially reduce the number of measure points to those, where the maximum relative variation of signals occur. In particular, it is important to remember that a higher relative displacement implies a higher risk for the stability of the heritage structure. As stressed before, this indicator has a limited validity in the context of a colonnade. Consequently, other indicators should be defined and used in other contexts.

Considering the established strengths and constraints of the results, the appropriateness of simulations for monitoring applications warrants careful consideration. The preliminary conclusions from the FEM simulations should be integrated into a cyclic process of optimization, aiming for the model's progressive adjustment, to align with the validated measurement data and for an optimization in terms of sensors number and positioning. Obviously, this optimization process should take into account the costs for managing the hardware system, including the sensors, the data transmission infrastructure, the data storage system, as well as all the other experimental requirements, needed to guarantee and effective functioning of the system. In parallel, the overall system characteristics should be defined, to support the wished data flows and the computation of results. The integrity of the input data and the modelling techniques and parameters, which in our investigation benefitted from prior empirical verifications cited in scholarly sources, can provide valuable insights. These insights are essential for the initial planning of monitoring frameworks to be implemented at archaeological sites or historically significant structures. Such sites, due to their nature, necessitate considerable resources, thereby underlining the need for their optimization.

In the proposed case, based on the available information and on the simulation outcomes, it would be possible, at the initial step of the monitoring system installation, prior to its optimization, to reduce the number of sensors. In particular, instead of monitoring both columns from the base to the connection between the capital and the epistyle, it could be possible to limit the measures from 660 m to the top-drum level or, considering the maximum expected acceleration or displacement, it could be possible to limit the initial installation on the column to two sensors (either at 660 m, for an acceleration measure, or at the top-drum level, for a displacement measure).

Then, an iterative upgrade process should take place, considering also that other factors should be assessed, including the nature of Soil-Structure Interaction, the morphology and materials of existing basement, the seismic input records, as well as the measure of any other relevant environmental parameter, such as the meteorological variables. This iterative process should include an improvement of the model on the basis of the monitoring system output, paralleled by an improvement of the sensors installation, in terms of type, number and positions, in order to improve a match between the simulated and observed signal frequencies and amplitudes. Similar matching methods, already used in the context of cultural heritage structures, are described in the literature [38], [39] .

An initial detailed survey, coupled with an evaluation of parameters and influencing factors previously noted, presents certain inherent limitations, which should be acknowledged. The simulations results are contingent upon the selected inputs, such as the seismic event, which, in reality, could comprise multiple factors (for instance, combining seismic signals with dynamic wind loads). Furthermore, the nature of the input influences the variability of the output. Therefore, to obtain reliable qualitative information, a series of historical scenarios should be analysed to understand the range of output variation. Despite these constraints, the described method, even when applied to a simplified scenario, has the potential to be expanded and assist in developing complex monitoring systems, provided there is access to comprehensive data on material properties and detailed structural morphology.

5. CONCLUSIONS

This work proposed an alternative use of FEM, consisting in its application to infer the preliminary metrological indications for a vibration monitoring system, in terms of expected signal amplitude and frequency, as well as of sensors positioning in the context of a heritage structure or infrastructure. The FEM is applied here to a classical Greek colonnade, whose scaled version was previously validated in the literature.

Notwithstanding the constraints intrinsic to FEMs, which demand precise parameterization and accurate signal input use, it is discernible from the results that certain aspects of a monitoring system's design can be deduced, including optimal sensor quantity and placement, alongside projected signal magnitudes. Prospective applications of this method may enhance the creation of 'phygital' systems that integrate monitoring technologies with a dynamically adaptive digital twin. This study findings underscore the feasibility of broader FEM application in the monitoring of the structural integrity of archaeological sites and monumental heritage. Specifically, simulations via digital twins could inform the development of their physical counterpart (i.e., the monitoring system), contributing to a dynamic method, that fosters proactive and informed preservation measures for cultural heritage structures and infrastructures.

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