Dynamic Response Assessment of the Acropolis Circuit Wall Using Structural-Health Monitoring, Big-Data Analytics, and Numerical Modelling

E. Kapogianni[1], P. Psarropoulos[2], G. Sakellariou[3], and M. Sakellariou[4]

[1]*Dr, National Technical University of Athens, Greece, email: elkapogianni@mail.ntua.gr*

[2]*Dr, National Technical University of Athens, Greece, email: prod@central.ntua.gr*

[3]*Dr, Independent Researcher, email: georgios.sakellariou@gmail.com*

[4]*Professor Emeritus, National Technical University of Athens, Greece, email: mgsakel@mail.ntua.gr*

ABSTRACT

Modern scientific methods play a key role in the preservation of Cultural Heritage, particularly when multiple approaches are combined. In the current study, a combined methodological framework is applied to the Acropolis of Athens, Greece, with a focus on the ancient Circuit (perimetre) Wall and its dynamic - seismic response. The Circuit Wall of the Acropolis of Athens functions as a masonry gravity retaining structure, supporting the backfill of the Hill plateau and ensuring the stability of the overlying monuments. This masonry gravity wall, constructed from mixed marble and stone, has been subjected over centuries to environmental degradation, human interventions, and repeated seismic loading, leading to locally observed structural distress. To assess its dynamic behaviour and seismic response, an advanced structural-health monitoring system based on Fibre Bragg Grating (FBG) optical sensors has been deployed on its southern section. The monitoring system includes strain, temperature and acceleration sensors, providing continuous, high-frequency measurements over an extended monitoring period. The present study focuses on the optical-fibre acceleration sensor, which generated large-volume time-series data requiring dedicated big-data ingestion, processing and transformation techniques. Custom data pipelines implemented using R statistical software were developed to efficiently manage, clean, store and analyse the high-frequency recordings, enabling frequency-domain investigation and long-term trend extraction. In parallel, two-dimensional finite-element numerical models of the Wall-backfill-bedrock system were developed to investigate its seismic response under idealised and recorded ground motions. The combined use of high-resolution optical-fibre acceleration measurements, advanced data analytics, and numerical simulations establishes an integrated framework for the assessment of the seismic behaviour of complex heritage structures. A comparison between the acceleration records obtained from the optical-fibre sensor and the results of the computational investigation is subsequently carried out, aiming to evaluate the consistency between measured and simulated responses and to enhance confidence in both monitoring and modelling approaches for cultural heritage preservation.

Keywords: Cultural Heritage Preservation; Acropolis of Athens; Masonry Retaining Wall; Structural-Health Monitoring; Fibre Bragg Grating (FBG) Sensors; Seismic Response; Big-Data Analytics; Frequency-Domain Analysis; Finite-Element Modelling.

INTRODUCTION

The Acropolis of Athens, one of the world's most significant archaeological sites, hosts numerous ancient monuments of great architectural and historical value, with the Parthenon being the most renowned. The structural integrity of all monuments on the Acropolis Hill is therefore crucial, not only for heritage conservation, but also for the safety of millions of visitors who attend annually. The Acropolis Hill rises approximately 150 m above sea level and 70 m above the city of Athens, exhibiting a trapezoidal shape with a length of around 300 m and width of approximately 150 m, situated 2 km southwest of Lycabettus Hill. Geologically, the Hill consists mainly of limestone overlying the softer Athenian schist. While limestone is exposed in areas not covered by artificial embankments, especially on the southern side, the schist is visible mainly at the archaeological entrance (Koukis et al., 2015). Karstification in the limestone has led to cavities that channel water, promoting localized erosion and rockfall phenomena. Over centuries, the Acropolis has also experienced multiple regional earthquakes, although structural damages have predominantly resulted from human interventions, environmental factors, and past restoration works rather than direct seismic impacts (Ambraseys, 2010).

Among the monuments of the Acropolis, the masonry Circuit Wall plays a crucial role in retaining the backfill materials that form the plateau surrounding the Parthenon. This irregular masonry retaining structure, approximately 800 meters long and ranging in height from 5 to 18 meters, encloses the plateau atop the Acropolis hill, providing essential structural support. Constructed mainly of marble and small stones, later repairs introduced mixed courses, especially in areas with prior damages. The southern part of the Wall, which reaches its greatest height (~18 m), retains poorly compacted backfill and has historically exhibited significant structural distress, including cracks and block detachments, particularly near the south-east corner, an area frequently used for transporting heavy restoration materials.

Given the Wall's structural complexity, varying geometrical properties, and the geological heterogeneity of the Hill, advanced methods are required to assess its condition and dynamic behaviour. Modern monitoring systems, including optical-fibre sensors and accelerographs, enable real-time recording of strain, temperature, and acceleration at multiple locations. This allows for early detection of potential damage and degradation mechanisms, as well as the evaluation of the Wall's response under operational and seismic loading conditions. Such approaches support the development of "smart" structures capable of proactive preservation and management, while the analysis of large datasets generated by these sensors facilitates informed decision-making regarding structural safety and long-term conservation strategies (Karanikoloudis et al, 2021; Abbiati et al, 2015; Gentile et al, 2007).

Additionally, computational simulations, such as those based on the finite-element method, constitute a powerful tool for investigating the structural behaviour of all structures, including monuments. They enable the detailed representation of complex geometries, heterogeneous materials, and boundary conditions, allowing for the numerical assessment of stress distribution, deformation patterns, and dynamic response under various loading scenarios. When combined with structural monitoring techniques, computational models can be calibrated and validated using in-situ measurements, significantly enhancing the reliability of the predicted structural response and supporting a more comprehensive understanding of the monument's behaviour.

In this study, a triple approach is applied to the Acropolis Circuit Wall, combining smart structural monitoring, high-frequency data analytics, and numerical modelling to assess its seismic response. Fibre Bragg Grating (FBG) optical-fibre sensors installed on the southern part of the Wall provide continuous, real-time measurements of strain, temperature and acceleration, with the present study focusing on the optical-fibre acceleration sensor (Kapogianni et al., 2016). The monitoring system has generated a large-volume time-series dataset, comprising high-frequency recordings from multiple sensors collected over nearly two years, which required dedicated big data management, processing and visualisation techniques to enable long-term trend analysis and reliable interpretation. Furthermore, two-dimensional finite-element simulations representing the Wall-backfill-bedrock system had been employed in the past to evaluate the dynamic response under seismic excitation, utilising recorded accelerograph data. The combined use of advanced sensing, computational modelling, and data-driven analysis supports a comprehensive assessment of the dynamic behaviour of the Circuit Wall.

Figure 1. *Overview of the Acropolis Hill, including the Circuit Wall, from the southeastern perspective.*

1. DEPLOYMENT OF THE OPTICAL-FIBRE ACCELERATION SENSOR

An optical fibre consists of a glass core surrounded by a cladding with a different refractive index, and an external polymer coating that provides protection against mechanical damage, moisture-related degradation, and crack growth. A Fibre Bragg Grating (FBG) sensor is a modified section of the optical fibre that reflects a specific narrow wavelength range while transmitting the remaining light. Variations in strain, temperature, or acceleration cause a corresponding shift in the reflected wavelength. When FBG sensors are installed at selected locations within a structure and monitored using suitable interrogation equipment, structural deformations can be measured accurately. Optical-fibre sensors offer high strain resolution, mechanical reliability, multiplexing capability, and compact dimensions, enabling their use on a wide range of structures.

As aforementioned, a comprehensive optical fibre-based structural-health monitoring system has been installed on the southern section of the Acropolis Circuit Wall to record strain, temperature, and acceleration variations, with particular emphasis in the present study on the FS65 optical fibre acceleration sensor installed at a height of approximately 2.5 m from the top of the Wall (Kapogianni et al, 2019). This monitoring array uses Fibre Bragg Grating (FBG) technology, enabling high-resolution, real-time measurements through wavelength shifts caused by dynamic loading. The southern part of the Wall was selected due to its structural significance, as it represents one of the tallest segments (approximately 18 m), retains a considerable volume of backfill, and exhibits visible cracking, indicating increased vulnerability. The proximity of the monitoring site to the existing accelerographic network on Acropolis Hill (Kalogeras et al., 2010) allows the integration of optical-fibre acceleration recordings with conventional accelerograph data and numerical simulations of the Circuit Wall, enabling a thorough assessment of its dynamic behaviour.

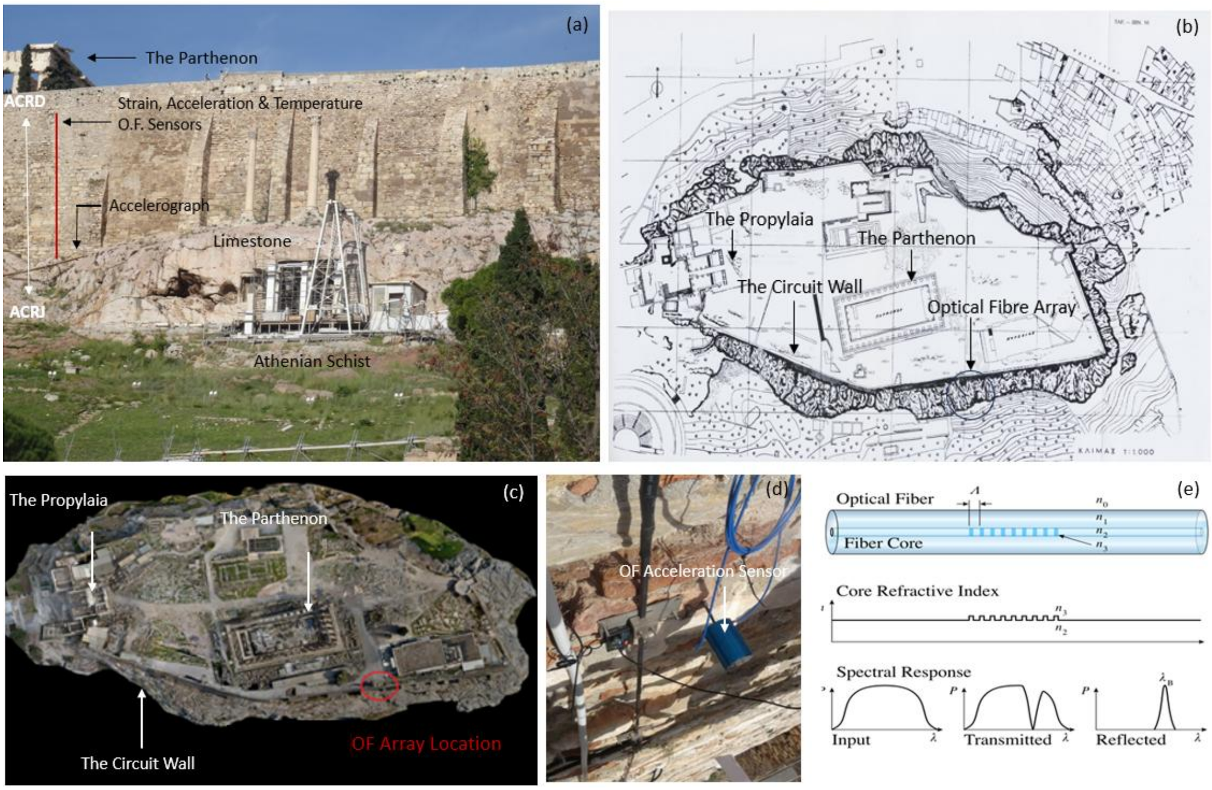

Figure 2. *Circuit Wall (a); plan view of the Acropolis Hill (b); location of the monitoring array (c); optical fibre (O.F.) acceleration sensor on the Wall (d); schematic of O.F. sensor operation (e).*

The FS65 accelerometer used in the current study has a reference wavelength of 1560.715 nm and a sensitivity of 17.703 pm/g, meaning that for every 1 g of acceleration, the FBG wavelength shifts by 17.703 pm (measured at the reference frequency of 40 Hz). The sensor exhibits a maximum relative calibration deviation of 0.4%, while the sensitivity remains stable across the full operating frequency range (0–50 Hz), with a flatness of 0.8%. Based on the manufacturer's specifications, the combined relative measurement uncertainty (accounting for calibration and flatness errors) was estimated using the RSS method and found to be approximately 0.9%. The sensor demonstrates high linearity, very low transverse sensitivity (<0.1%), and is capable of measuring accelerations up to ±10 g, enabling accurate detection of low-amplitude seismic excitations. A detailed summary of the sensor's technical specifications is provided in Table 1.

Table 1. Optical-Fibre Accelerograph Specifications

Specifications	
Sensitivity	17.703 pm/g @ 40 Hz
Measurement range	± 10 g
Frequency range	0 to 50 Hz
Resonance frequency	430 Hz
Flatness	< 2%
Resolution	12.5 μg/√Hz
Maximum calibration error	±0.1 g @ 40 Hz
Transverse sensitivity	< 0.1%

Based on the sensor specifications, the acceleration A corresponding to a measured wavelength shift $\Delta\lambda_i$ can be calculated using a linear proportional relationship,

$$A = (\Delta\lambda_i)/S \quad (1)$$

where A is the acceleration expressed in units of g, $\Delta\lambda_i$ is the measured wavelength shift in picometers (pm), and S=17.703 pm/g is the sensitivity of the FS65 sensor. To express the acceleration in SI units, the measured wavelength shift is converted to acceleration in m/s² according to

$$a_i = (\Delta\lambda_i)/S*g \quad (2)$$

where a_i is the acceleration in m/s² and g = 9.81m/s^2 is the standard gravitational acceleration.

To ensure accurate acceleration measurements, temperature effects must be taken into consideration, as temperature variations can induce wavelength shifts similar to those caused by acceleration. These temperature-induced wavelength shifts are not related to acceleration and must therefore be removed from the total measured wavelength shift. The acceleration-related wavelength shift is obtained as

$$\Delta\lambda_{acc} = \Delta\lambda_{total} - \Delta\lambda_T \quad (3)$$

where $\Delta\lambda_{total}$ is the measured total wavelength shift, $\Delta\lambda_T$ is the wavelength shift caused by temperature variations, and $\Delta\lambda_{acc}$ is the wavelength shift due solely to acceleration. Once the temperature contribution has been removed, the corrected acceleration is calculated using the following equation

$$a=(\Delta\lambda_{acc})/S *g \quad (4)$$

For the purposes of the present study, an analysis was performed on representative high-frequency time-series segments, without applying all possible correction and conversion procedures described above, which are nonetheless presented in this article as a methodological reference framework. This choice was motivated by the objective of achieving a first-order visualisation and spectral interpretation of large acceleration datasets, serving as an initial step toward the systematic analysis and full physical calibration of long-term monitoring records.

2. EXTRACTION OF STRUCTURAL-HEALTH INSIGHTS

The dataset analysed in this paper comprised time-series data exported in raw text format from optical fibre sensors, capturing readings from a single sensor at a frequency of 200 measurements per second for a period of almost 24 hours. As a result, conventional toolsets quickly presented insurmountable limitations with respect to data windowing and transformation. The authors selected the R language for designing and building a custom data pipeline due to its memory-efficient processing capabilities. Data ingestion and transformation comprised a script that extracted time-series data from text files using optimised functions, rather than base R alternatives, and converted into a serialised format for more efficient manipulation. Such choices were necessary due to the volume of data available, as well as their segmentation into multiple files which introduce further inefficiencies. For the purposes of this study, the ingestion process resulted in a data frame counting 17.2 million rows.

Next, the data needed to be transformed into the frequency domain to extract meaningful insights relating to the objectives of this research. Data pre-processing involved subtracting the mean of the first thousand samples from the signal, in effect acting as a de-noising step. Subsequently, a “Fastest Fourier Transform in the West” (Frigo & Johnson, 2005) implementation was compiled from source code in order to accommodate the compute platform available to us, reducing the Fast Fourier Transform computation lead time from hours to seconds. In turn, this method allowed for the inclusion of the entire sample size in the frequency domain calculations, which facilitated higher frequency resolution. Last, the transformed signal magnitude was converted into a logarithmic scale to better capture the entirety of its dynamic range. The steps described above have yielded three novel findings as a direct result of the methodology followed on Acropolis Circuit Wall data:

1. A broad-spectrum view that captures the range between 0-15Hz showcases the effectiveness of the data capture and processing methodology. Clear spikes can be seen alongside lower magnitude frequencies (Figure 3a).
2. The first major spike is detected in the region of 7.8Hz. Qualitative characteristics that include a magnitude build-up at neighbouring frequencies are strong indicators of resonance and in agreement with other methods presented elsewhere in this paper (Figure 3b).
3. A spike at 8Hz can also be seen, although this may be a finding of potentially secondary consequence (Figure 3c).
4. The large sample size facilitated further isolation of the dominant peak with even higher precision revealing resonance in the region of 7.8Hz (Figure 3d).

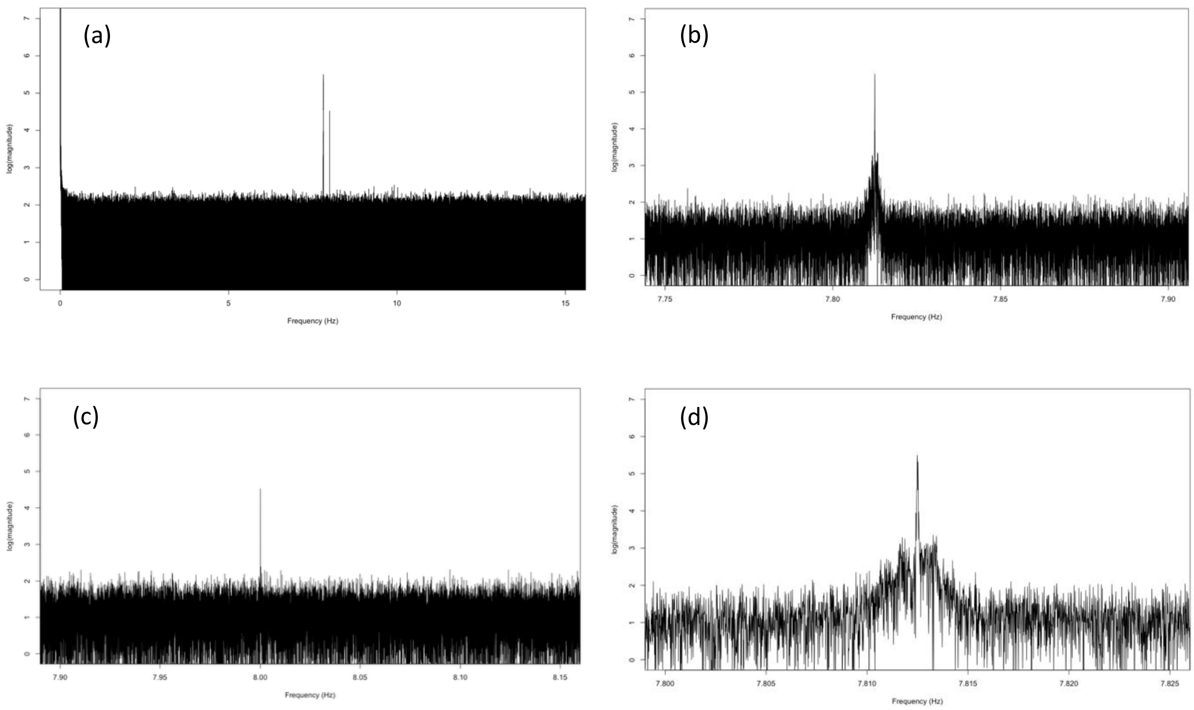

Figure 3. *Frequency-domain analysis of optical-fibre acceleration recordings at the Circuit Wall: broadband spectrum in the 0–15 Hz range (a); detailed view highlighting the dominant resonance peak at approximately 7.8 Hz (b); secondary spectral peak observed near 8 Hz (c); View of dominant peak with elevated frequency resolution revealing resonance with higher precision in the region of 7.8Hz (d).*

3. NUMERICAL SIMULATION OF THE CIRCUIT WALL

Over the last decades, the seismic ground motion of the Acropolis Hill and the dynamic response of its monuments are monitored by a network of ten accelerographs installed at selected locations on the ground surface and on the monuments (Kapogianni et al, 2021). In the area of the southern Wall, two accelerographs are installed at the base (ACRD) and at the top (ACRJ) of the Wall, enabling direct comparison of the seismic response along its height. From the available recordings, two seismic events were selected for analysis: (a) a strong far-field earthquake with predominantly low-frequency content, and (b) a weak near-field earthquake characterized by higher-frequency components.

During the regional event the acceleration time histories recorded at the base and at the top of the Wall are comparable, exhibiting long duration and nearly identical peak ground acceleration values. In contrast, the near-field event shows shorter duration and lower peak ground acceleration, while the acceleration levels recorded at the top of the Wall are significantly higher than those at the base, indicating pronounced local amplification effects.

Analysis in the frequency domain further highlights these differences. The Fourier spectra at the base of the Wall show that the regional earthquake is dominated by low-frequency components, whereas the near-field event exhibits low spectral amplitudes across the entire frequency range. At the top of the Wall, the regional event remains low-frequency dominated, while the near-field earthquake displays increased spectral amplitudes at high frequencies. For the regional event, the spectral amplitudes at the base and the top of the Wall are similar, whereas for the near-field event the spectrum at the top is substantially amplified relative to that at the base in the high-frequency range. The amplification factor, AF, defined as the ratio of the Fourier spectrum at the top of the Wall to the corresponding spectrum at its base, indicates negligible amplification at low frequencies and significant amplification at high frequencies. The Fast Fourie Transform of the accelerations recorded at the base and the top of the wall for the two mentioned seismic events can be found in Psarropoulos et al (2018). Despite the differences between the two seismic motions, comparable amplification levels are observed, as the amplification factor primarily depends on the geometric and mechanical properties of the wall-soil system under linear elastic conditions.

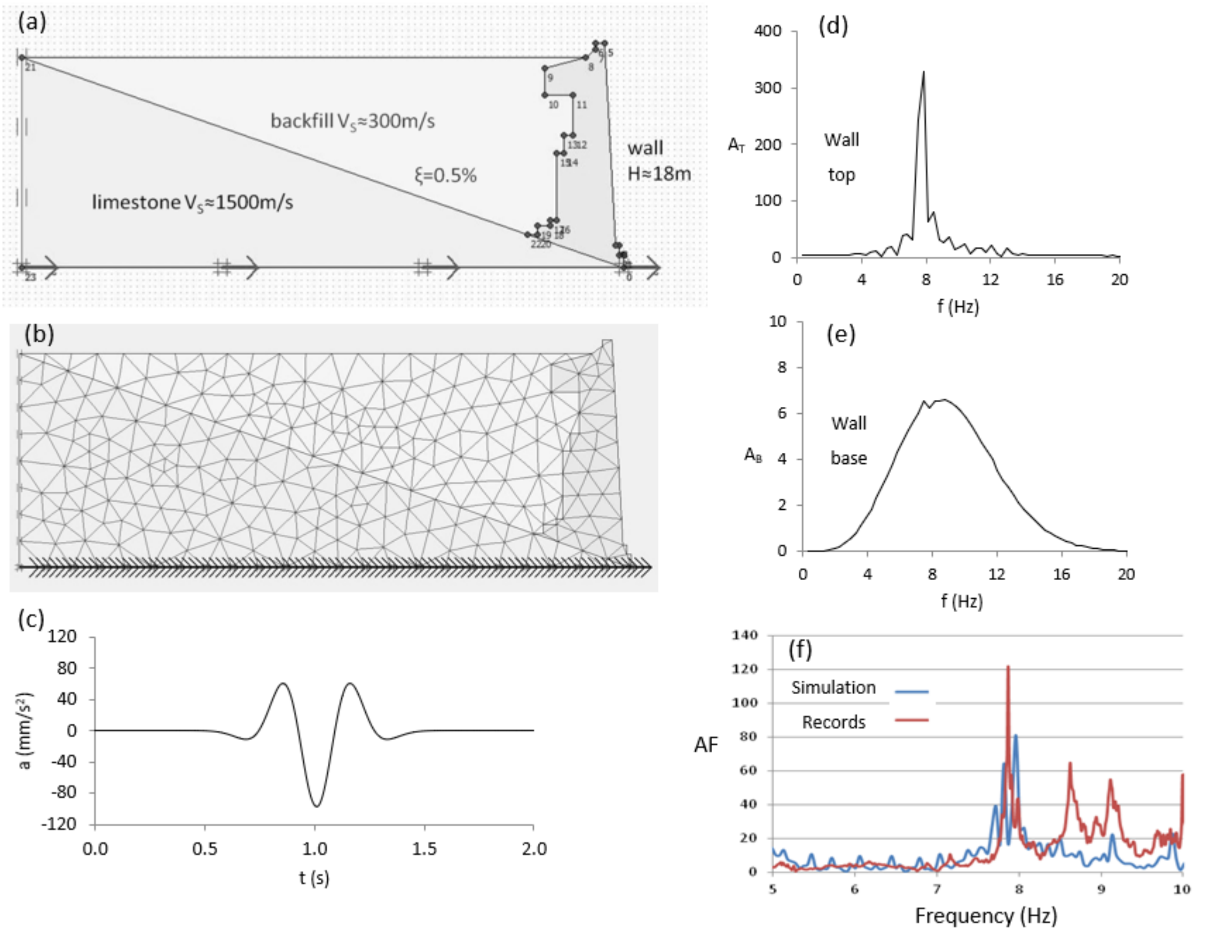

Figure 4. *Two-dimensional numerical model and dynamic response of the southern Circuit Wall: (a) geometry and mechanical properties, (b) finite-element discretization, (c) input acceleration time history at the Wall base (Ricker pulse), (d) Fourier spectrum of the response at the top of the Wall, (e) Fourier spectrum of the response at the base of the Wall, and (f) comparison between recorded and computed amplification factors (AF) under near-field seismic excitation.*

To assess the seismic response of the southern Circuit Wall, a realistic two-dimensional finite-element model was developed at the location of the ACRD and ACRJ accelerograph stations. The model geometry and the corresponding finite-element discretization were implemented using the commercial finite-element software PLAXIS, which is capable of simulating the dynamic response of two-dimensional systems under seismic loading. The mechanical properties of the limestone and the backfill material were defined based on available data and values reported in the literature. Given the low acceleration levels of the examined seismic excitations, the system response was assumed to be linear elastic, and a low Rayleigh damping ratio of 0.5% was adopted in all numerical analyses. With regard to the seismic input motions, two sets of analyses were performed, (a) initially, idealized Ricker pulses were applied, as they cover a broad frequency range and allow a reliable estimation of the amplification factor in the frequency domain, and (b) numerical analyses were carried out using recorded acceleration time histories at the base of the Wall as input motions. Following the Ricker pulse simulations, the recorded base accelerations were used as input motions to further investigate the system response. Since Rayleigh damping is frequency-dependent, two damping formulations with the same damping ratio but different frequency ranges were examined. The results indicate that the definition of Rayleigh damping can influence the calculated amplification factors, particularly in the high-frequency range. Despite discrepancies between numerical results and recorded data, mainly attributed to model simplifications and uncertainties in material properties, the numerical simulations are considered satisfactory for capturing the main features of the seismic response of the wall-soil system. Figure 4 demonstrates the numerical model based on Trikkallinos (1972) and the assumption of the shear wave velocity of the backfill equal to 300 m/sec along with indicative results of the numerical simulation.

4. COMPARISON OF OPTICAL-FIBRE MEASUREMENTS AND NUMERICAL PREDICTIONS

A direct comparison between the optical-fibre acceleration measurements and the numerical predictions can provide valuable insight into the dynamic behaviour of the Circuit Wall. The frequency-domain analyses derived from the optical fibre acceleration recordings consistently reveal a dominant spectral peak at approximately 8.0 Hz, which is interpreted as a phenomenon associated with the Wall response. The numerical simulations, based on a two-dimensional finite-element representation of the Wall-soil system, yield amplification functions that exhibit a peak within the same frequency range. In particular, the amplification spectra computed at the top of the wall relative to its base show maximum values around 8 Hz, in close agreement with the observed dominant frequency obtained from the optical fibre measurements. This convergence is observed both in the analyses employing idealised Ricker pulse excitations and in those using recorded seismic motions as input.

Despite differences in absolute amplitude levels between the numerical results and the recorded data, the overall spectral shape and the location of the dominant frequency are quite consistent. These discrepancies in amplitude can be attributed to inevitable simplifications in the numerical model, uncertainties in material properties, and assumptions related to damping formulation. Nevertheless, the agreement in the frequency content indicates that both approaches capture the same fundamental dynamic mechanism governing the response of the system.

The coincidence of the dominant frequency identified independently through in situ optical fibre measurements and numerical simulations strongly suggests that the observed peak at approximately 8 Hz corresponds to the fundamental natural frequency of the combined Wall-backfill system. This finding supports the interpretation that the dynamic response is controlled by the interaction between the masonry wall and the retained soil mass, acting as an integrated geotechnical-structural system. Overall, the combined use of high-resolution optical-fibre acceleration monitoring and numerical modelling proves effective in identifying key dynamic characteristics of the Circuit Wall.

CONCLUSIONS

The present study demonstrated the effectiveness of an integrated and multidisciplinary framework that combines optical fibre-based structural health monitoring, big-data analytics, and numerical modelling for the dynamic assessment of the Acropolis Circuit Wall. By focusing on the southern section of the Wall, which represents one of its most structurally critical and vulnerable segments, the study provided valuable insight into the dynamic behaviour of a complex masonry retaining structure that supports both the Acropolis Hill plateau and the overlying monuments.

High-frequency acceleration time histories were derived from wavelength shift recordings obtained by a Fibre Bragg Grating (FBG) optical-fibre acceleration sensor. The analysis highlighted the suitability of optical-fibre sensing technology for long-term monitoring of heritage structures, particularly in environments where conventional sensors may be intrusive or difficult to deploy. Emphasis was placed on the identification of dominant frequency components rather than on absolute acceleration amplitudes, allowing reliable extraction of dynamic characteristics from the available measurements.

Frequency-domain analysis of the optical-fibre acceleration recordings consistently revealed a dominant spectral peak in the range of approximately 7.8-8.0 Hz. Independent two-dimensional finite-element simulations of the wall-backfill-bedrock system, subjected to both idealised Ricker pulses and recorded seismic excitations, exhibited amplification peaks within the same frequency range. Despite discrepancies in absolute amplitude levels, which can be attributed to unavoidable modelling simplifications, uncertainties in material properties, and assumptions related to damping formulation, the agreement in the identified dominant frequency strongly suggests that this peak corresponds to the fundamental natural frequency of the combined masonry wall-backfill system. The convergence between measured and numerically predicted frequency characteristics indicates that both approaches capture the same governing dynamic mechanism. This finding reinforces confidence in the reliability of both the monitoring system and the numerical modelling strategy, while also highlighting the potential of in situ monitoring data to support model calibration and validation.

Overall, the results underline the critical importance of integrating structural-health monitoring, big-data analytics, and numerical modelling, demonstrating that the combination of these three complementary approaches enables a comprehensive dynamic characterization of complex heritage structures. Beyond the specific case of the Acropolis Circuit Wall, the methodology presented in this study is transferable to other monumental structures and heritage retaining systems, offering a useful tool for long-term preservation of culturally significant sites subjected to seismic hazard.

REFERENCES

Abbiati, G., Ceravolo, R., & Surace, C. (2015). Time-dependent estimators for on-line monitoring of full-scale structures under ambient excitation. *Mechanical Systems and Signal Processing,* 60–61, 166–181.

Ambraseys, N. (2010). On the long-term seismicity of the city of Athens. *Proceedings of the Academy of Athens, Vol. A*, 81–136.

Frigo, M., & Johnson, S. G. (2005). The design and implementation of FFTW3. *Proceedings of the IEEE, 93*(2), 216–231. Invited paper, Special Issue on Program Generation, Optimization, and Platform Adaptation.

Gentile, C., & Saisi, A. (2007). Ambient vibration testing of historic masonry towers for structural identification and damage assessment. *Construction and Building Materials, 21*(6), 1311–1321.

Kalogeras, I., Stavrakakis, G., Melis, N., Loukatos, D., & Boukouras, K. (2010). The deployment of an accelerographic array on the Acropolis hill area: Implementation and future prospects. *Proceedings of a One-Day Conference, Modern Technologies in the Restoration of the Acropolis, Athens, Greece*, 39–42.

Kapogianni, E., Psarropoulos, P. N., Kokoris, D., Kalogeras, I., Michalopoulou, D., Eleftheriou, V., & Sakellariou, M. (2021). Impact of local site conditions on the seismic response of the Athenian Acropolis Hill. *Geotechnical and Geological Engineering, 39*(3), 1817–1830.

Kapogianni, E., Kalogeras, I., Psarropoulos, P., Eleftheriou, V., & Sakellariou, M. (2019). Suitability of optical fibre sensors and accelerographs for the multi-disciplinary monitoring of a historically complex site: The case of the Acropolis Circuit Wall and Hill. *Geotechnical and Geological Engineering, 37*(5), 4405–4419.

Kapogianni, E., Kalogeras, I., Psarropoulos, P. N., Giokaris, S., & Sakellariou, M. G. (2016). Structural health monitoring of the Athenian Acropolis' Walls via optical fibre sensors, accelerographs and numerical simulations. In K. Van Balen & E. Verstrynge (Eds.), *Structural analysis of historical constructions: Anamnesis, diagnosis, therapy, controls* (pp. 701–707). Boca Raton, FL: CRC Press, Taylor & Francis Group.

Karanikoloudis, G., Lourenço, P. B., Mendes, N., Serra, J. B., & Boroschek, R. (2021). Monitoring of induced groundborne vibrations in cultural heritage buildings: Miscellaneous errors and aliasing through integration and filtering. *International Journal of Architectural Heritage, 15*(1), 205–228.

Koukis, G., Pyrgiotis, L., & Kouki, A. (2015). The Acropolis Hill of Athens: Engineering geological investigations and protective measures for the preservation of the site and the monuments. In *Engineering Geology for Society and Territory - Volume 8* (pp. 89–93).

Psarropoulos, P., Kapogianni, E., Kalogeras, I., Michalopoulou, D., Eleftheriou, V., Dimopoulos, G., & Sakellariou, M. (2018). Seismic response of the Circuit Wall of the Acropolis of Athens: Recordings versus numerical simulations. *Soil Dynamics and Earthquake Engineering, 113*, 309–316.

R Core Team (2021). R: A language and environment for statistical computing. *R Foundation for Statistical Computing*, Vienna, Austria.

Trikkalinos, I. K. (1972). The geology of the Acropolis. Proceedings of the Academy of Athens.