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Integrated structural condition assessment of an ancient Mayan Temple

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ABSTRACT

The Temple of the Masks, also known as Temple II, is a significant funerary and ceremonial structure built by the Maya around 700 AD. Located in Tikal, the largest city of the Classic Maya period in the Petén region of northern Guatemala, its preservation is crucial. Given the delicate nature of archaeological sites, continuous monitoring of the temple's structural and dynamic properties is essential to protect its integrity and ensure long-term conservation. This study presents a detailed assessment of the temple using ambient vibration field measurements to identify modal frequencies, damping ratios, and mode shapes. These parameters establish a structural baseline essential for detecting future changes that could indicate damage or deterioration. In addition, the study considered a 3D laser scanner of the temple to complement these evaluations. This high-resolution, non-invasive technique captured precise geometric data through a cloud point, enabling assessment of any misalignment in the structure that might signal underlying issues. Following the geometric survey, a simplified model was calibrated, integrating the structure's dimensions, dynamic properties, and results from sclerometric tests, which measured the mechanical strength of the temple's stone material. This multifaceted approach demonstrates the importance of using a combination of monitoring tools to preserve archaeological structures effectively. This study provides a robust framework for conserving the Temple of the Masks by uniting ambient vibration analysis and precise geometric modelling. The calibrated model created from this data serves as a valuable tool for ongoing stability assessments and underscores the role of advanced, complementary technologies in heritage monitoring, offering a technically robust strategy to protect and preserve culturally significant structures like Temple II at Tikal.

Keywords: Structural health monitoring, 3-D laser scanning, heritage conservation, surveying, sclerometric test, calibration model, ambient vibration.

1. INTRODUCTION

1.1. Significance of the Temple of the Masks in Tikal

The Temple of the Masks, or Temple II, is one of the most iconic structures in Tikal, located in the Peten region of northern Guatemala. Built around 700 A.D., it reflects the architectural and ceremonial sophistication of the Maya civilization during the Classic Period. Positioned on the western side of the Great Plaza, opposite the equally famous Temple I, it was likely constructed to honor Lady Kalajuun Une' Mo', the wife of King Jasaw Chan K'awiil I. This temple holds architectural significance and represents a period of political and cultural revitalization in Tikal [4]. Preserving Temple II is crucial due to its historical importance and the environmental challenges it faces. As highlighted by Rossi and Bournas [3], monitoring and managing the structural health of heritage sites is essential to their long-term conservation. Modern Structural Health Monitoring (SHM) techniques, like vibration analysis and laser scanning, provide critical insights into structural performance and potential deterioration. These tools, combined with methods such as material testing and soil-structure interaction studies, create a comprehensive approach to preservation. In the case of Temple II, its location on potentially unstable soil adds another layer of complexity to its preservation. Soil-structure interaction, often overlooked in heritage conservation, plays a significant role in the stability of structures like this. Researchers such as Sangirardi et al. [1] and Aguilar et al. [2] emphasize the need for interdisciplinary approaches that combine structural analysis with geotechnical insights. These methods help address current issues and potential future risks to the monument. Moreover, Temple II is not just a ceremonial and architectural masterpiece; it is also connected to Maya cosmology and astronomical practices. Studies by Sprajc [5] highlight the importance of astronomical alignments in Maya architecture, offering further evidence of the temple's cultural and spiritual significance. This adds another dimension to its preservation, making it a priority to study and conserve this unique site holistically. Integrating techniques like ambient vibration monitoring, geometric survey through laser scanning, and computational modelling makes it possible to create a detailed understanding of the temple's current condition. This comprehensive approach, as supported by the methodologies discussed in Rossi and Bournas [3], ensures that Temple II remains a vital part of our shared cultural heritage for future generations.



Figure 1. Left: Geographical location of Tikal National Park (red squared). Upper-right: The Temple of the Masks (Temple II), evaluated in this research. Downright: Temple of the Great Jaguar (Temple I)

1.2. Importance of monitoring structural integrity for archaeological preservation

Preserving archaeological monuments like Temple II in Tikal presents numerous challenges, including the lack of detailed architectural documentation, the absence of data on material degradation rates, and limited records of the impacts of natural disasters or climatic changes. These gaps complicate

conservation efforts and increase the vulnerability of heritage structures to undetected damage or progressive deterioration. Structural Health Monitoring (SHM) has emerged as a vital approach to address these issues, providing robust quantitative data that informs decision-making and supports sustainable preservation strategies. SHM integrates advanced tools such as ambient vibration monitoring, 3D laser scanning, drone-based photogrammetry, and ground-penetrating radar (GPR) to assess the condition of cultural heritage structures. Ambient vibration monitoring, for example, identifies key dynamic properties such as modal frequencies, damping ratios and modal shapes, which establish baselines for detecting structural changes over time [6], [7]. Meanwhile, 3D laser scanning offers high-resolution geometric data, enabling the detection of structural misalignments or deformations, and drones facilitate efficient and accurate photogrammetric surveys of areas that are difficult to access [8][9][16]. Ground penetrating radar (GPR) provides subsurface data, revealing potential risks such as soil instability or hidden voids, which are crucial for understanding the interaction between the structure and its foundation [10]. Recent advancements in SHM have further enhanced its applicability by developing digital twins—virtual models that integrate real-world data to simulate and predict structural behavior. These models allow researchers to analyze the effects of environmental events, such as earthquakes or extreme weather, and evaluate the potential outcomes of conservation interventions before their implementation. Darwish et al. [11] highlight how digital twins, coupled with IoT technologies, provide a dynamic and adaptive framework for heritage conservation. In summary, SHM is an indispensable tool in preserving cultural heritage. Its combination of advanced monitoring technologies and analytical models bridges knowledge gaps, provides actionable insights for conservation efforts, and aligns with the broader goals of sustainable and informed heritage management. For sites like Temple II, SHM ensures not only the stability of the structure but also the continuation of its cultural and historical legacy.

2. ON-SITE ASSESSMENT METHODOLOGY

2.1. Ambient vibration tests

A series of ambient vibration tests were conducted at the temple to determine their dynamic modal properties. Nine portable-wireless sensors [14] were used for these tests. The testing program consisted of three measurement setups. The layouts of the sensors are illustrated in Figure 2. For all configurations, five out of nine sensors were considered as reference: four at level 3 and one at the ground level. The remaining four sensors were placed at level 2 for setup 1, at level 1 for setup 2 and level 4 for setup 3 as rovers. The duration for all setups was 20 minutes at 128 Hz.

2.2. Sclerometric tests

Schmidt hammer tests were performed at 64 points on the pyramid to establish a characteristic value for the compressive strength of the material. The method provides a non-destructive estimation of compressive strength by measuring the rebound number, which correlates with material hardness and strength. The relationship between the rebound number and compressive strength is established empirically and can be expressed as $f_c = a \cdot R^b$, where f_c is the compressive strength, R is the rebound number, and a and b are material-specific constants.

2.3. 3D Geometric Survey

A laser scanning survey was conducted around the entire perimeter of the pyramid to achieve a detailed three-dimensional model based on a point cloud. Thirty-one positions were performed using equipment capable of capturing 360,000 points per second, ensuring high-resolution data collection (Figure 3). This technique enabled the accurate capture of the pyramid's geometry, including its external contours and structural features. The point cloud data was processed to generate a 3D representation, considered as a reference for further structural and geometric analysis. Additionally, the laser scanning data was utilized to monitor the verticality of the pyramid by assessing any deviations from its theoretical vertical axis. This evaluation provides critical insights into potential tilting or leaning of the structure. Furthermore, the survey was employed to detect and quantify differential settlements, which may affect the stability and integrity of the pyramid. By combining geometric modelling with monitoring these

structural aspects, the methodology ensures a comprehensive understanding of the current condition of the pyramid and long-term stability.

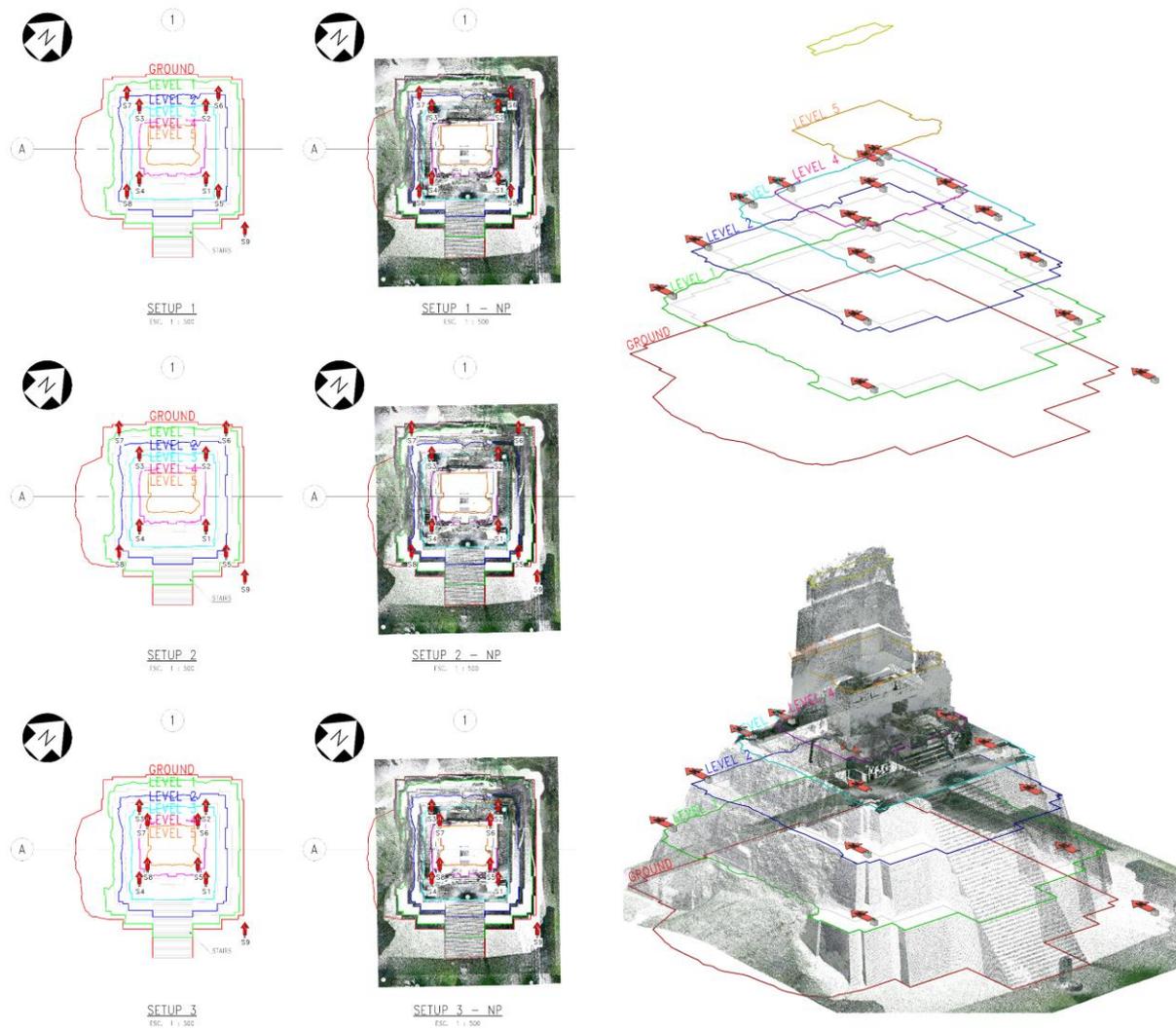


Figure 2. Setup 1 to 3. Ambient vibration test setup (velocity).

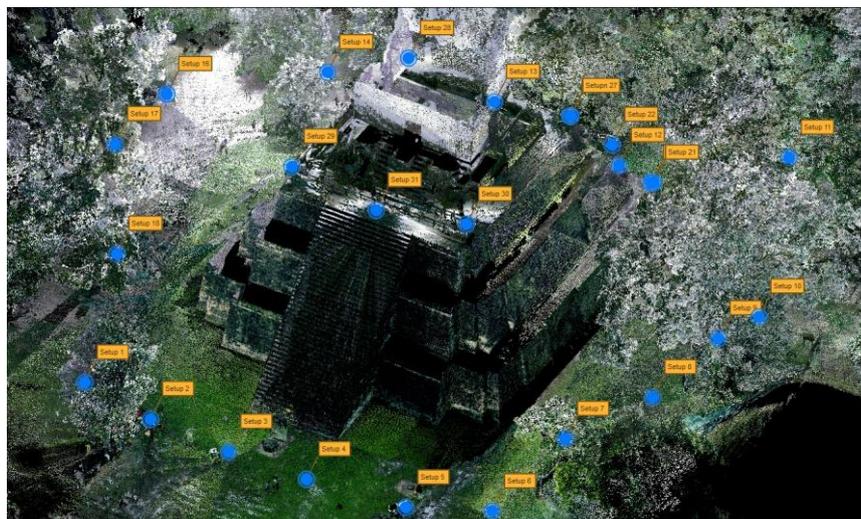


Figure 3. Laser Scanner Positions during survey

3. RESULTS AND DISCUSSION

3.1. Dynamic properties

Well-established techniques were employed in both the frequency and time domains to obtain the dynamic parameters of the temple. The Enhanced Frequency Domain Decomposition (EFDD) was used for the frequency domain. For the time domain analysis, the Stochastic Subspace Identification (SSI) approaches—Unweighted Principal Components (UPC) and Canonical Variate Analysis (CVA)—were applied. All the analyses were developed using the ARTeMIS Modal software [15]. The results obtained from these analyses are presented below.

Table 1. Frequencies (f) and damping ratios (β). Ambient vibration tests (setup 1-2-3).

N°	Freq. [Hz] EFDD	Freq. [Hz] SSI-UPC	Freq. [Hz] SSI-CVA	Freq. [Hz] Avg.	β [%] EFDD	β [%] SSI-UPC	β [%] SSI-CVA	β [%] Avg.	Predominant Direction Modal Shape
1	4.07	4.08	4.07	4.07	0.5	1.6	1.0	1.0	Bending
2	4.24	4.26	4.24	4.25	1.2	2.2	1.8	1.7	Bending
3	5.32	5.28	5.29	5.30	1.0	2.2	2.5	1.9	Bending
4	5.94	5.95	5.94	5.94	0.8	2.4	1.9	1.7	Torsion

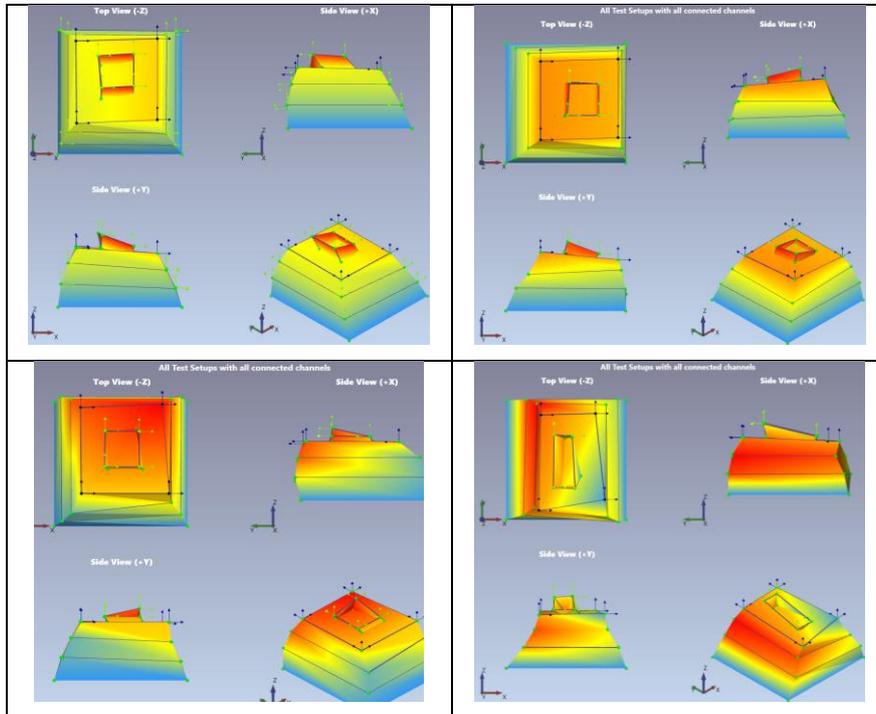


Figure 4. Modal Shapes. Upper-left: $f=4.07$ [Hz], upper-right: $f=4.25$ [Hz], down-left: $f=5.30$ [Hz], down-right: $f=5.94$ [Hz]. ARTeMIS Modal [15].

3.2. Sclerometric tests

According to the study by García de Miguel et al. [12], the structure of the Great Jaguar Pyramid, close to the Temple II consists of ashlar masonry walls filled with “*embono*”, a lime mortar with local limestone fragments, forming a solid system with minimal voids. The fine-grained limestone used in the masonry is highly porous, making it susceptible to erosion and biological growth. While the study conducted by García de Miguel et al. [12] focuses on the Great Jaguar Pyramid, its findings are extendable to Temple II, as both share the same construction techniques and materials. The deterioration processes identified, such as loss of “*embono*” cohesion and limestone degradation, are also likely present in Temple II, providing valuable insights for its study and conservation

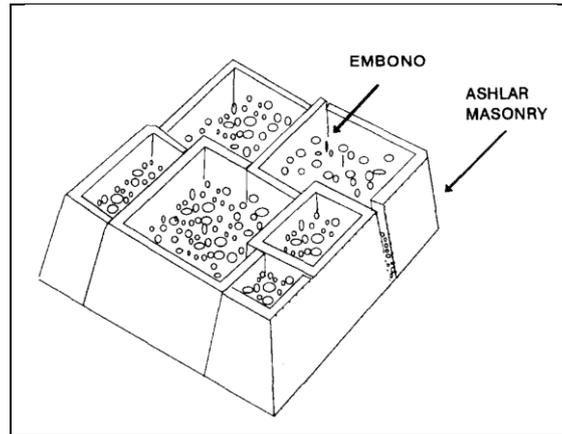


Figure 5. The schematic material structure of the Temple. [12]

Based on M. Krzan et al. [13], the compressive strength of ashlar masonry varies depending on the morphology and construction quality. The average compressive strength of ashlar stone masonry walls tested in that study was 6.05 MPa. Additionally, the literature review in the document provides a broader range of compressive strength values for different types of ashlar masonry, generally ranging from 4.0 MPa to 8.0 MPa, depending on the type of stone and mortar used.

The results obtained during the assessment of the Temple II from Schmidt hammer (sclerometric) indicate an average compressive strength of 6.6 MPa, which correlates acceptably with the study developed by Krzan et al. [13]. However, as shown in Figure 6, a high heterogeneity is observed, with values ranging between 4 MPa and 12 MPa. This variability is also consistent with the study conducted by M. Krzan et al. [13], supporting the establishment of a correlation between rebound number and compressive strength.

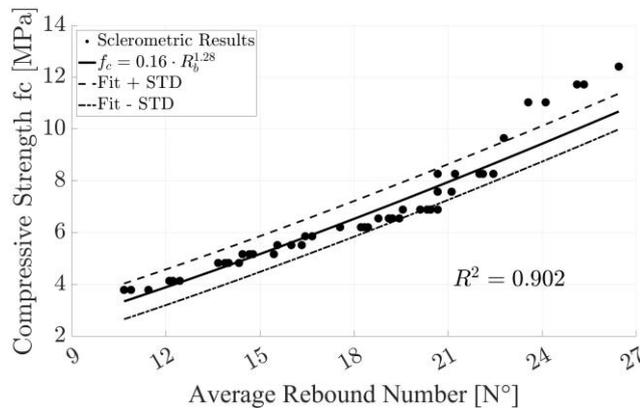


Figure 6. Left: Sclerometric results and correlation equation between rebound number and compressive strength. Right: Schmidt Hammer Test on-site.

3.3. Geometry Survey

The laser scanning survey provided an extensive and detailed dataset, enabling a comprehensive analysis of the pyramid's geometry and structural behaviour. The 3D point cloud generated through the survey captured the majority of the pyramid's dimensions with high precision, both in plan and elevation. This level of detail allowed for an in-depth evaluation of the structure's external contours, vertical alignment, and overall stability.

A key finding from the analysis was the identification of differential settlements (or rocking) within the pyramid. These settlements were quantified across its structural blocks, revealing a progressive decrease in settlement values from the base to the upper sections. Specifically, the first block (base) exhibited a differential settlement of 278 mm, the second block (between level 1 and 2) 169 mm, and the third block (between level 2 and 3) 68 mm. These differential settlements must be considered for a structural evaluation. In the opposite direction, no differential settlements were found.

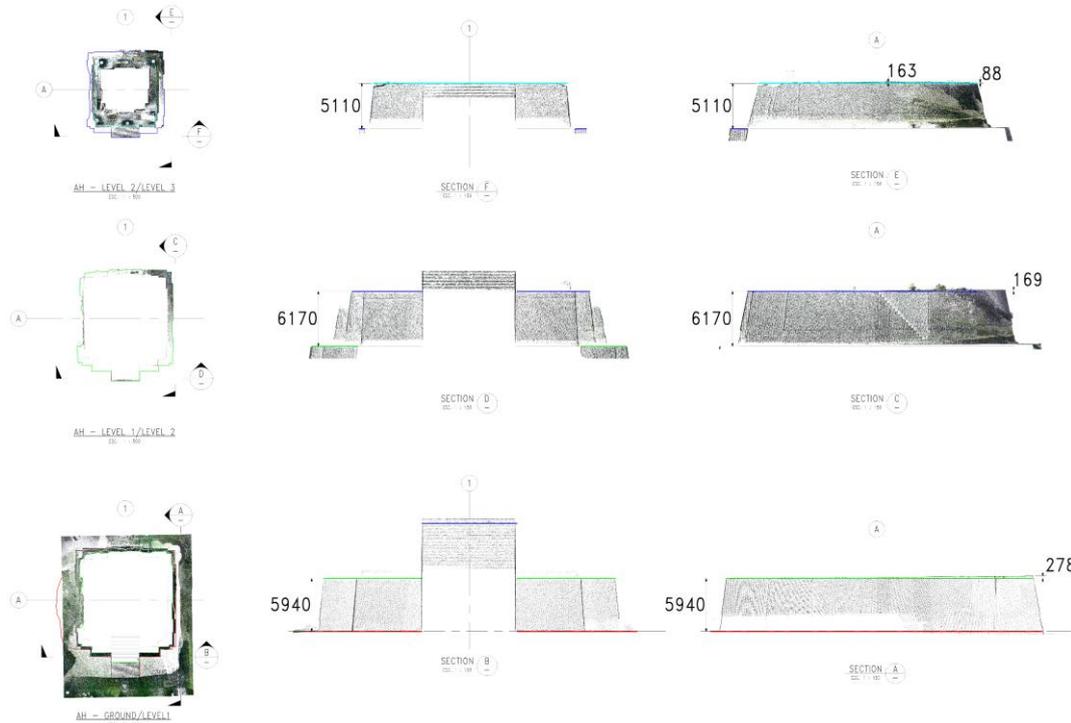


Figure 7. Estimated rocking between pyramid blocks using 3D laser scanning. Up: upper block, between level 3 and 2. Middle: middle block, between level 2 and 1. Down: ground block, between level 1 and ground.

3.4. Calibrated Model

One of the most common applications following a structural assessment and SHM analysis is the calibration of a mathematical model to evaluate the structural condition. A structural model also enables simulations to assess performance under events like earthquakes, soil effects (e.g., liquefaction), extreme climatic events (flood, hurricanes, etc.) or even degradation over time. In this case, a simplified three-degree-of-freedom model was developed, incorporating the geometric and estimated strength results. An extra mass corresponding to the pyramid's crowning was included in the system to account for its influence on the dynamic behavior.

For the most simplified case, the following values were considered:

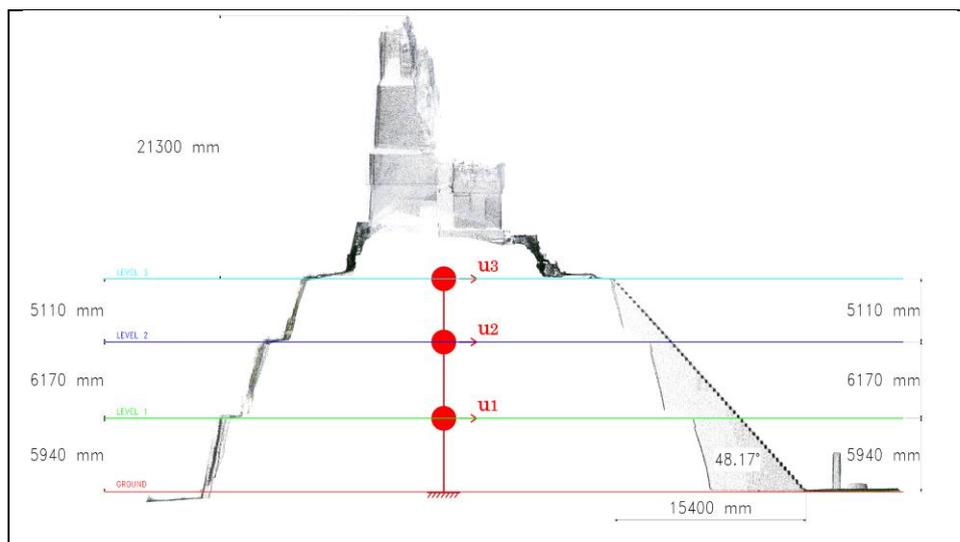


Figure 8. Simplified model scheme (2-D, three displacement DOF)

Table 2. Calibrated mechanical properties for simplified model.

N°	Variable	Symbol	Value	Unit	Comments
1	Density	γ	2025	kg/m^3	Calibrated base on clay soils improved with lime or cement: 1700 - 2200 kg/m^3
2	Compressive Strength	f'_c	6.68	MPa	Average value from sclerometric test
3	Young's Modulus	E	983	MPa	$E = 150 \cdot f'_c$
4	Poisson's Retio	ν	0.15	MPa	Calibrated base on clay soils improved with lime or cement: 0.15 - 0.35
5	Shear Modulus	G_c	427	MPa	$G_c = \frac{E}{2(1 + \nu)}$

The density shown in Table 2 is based on the work of M. Kržan & V. Bosiljkov (2023) [13], while the compressive strength was obtained from in-situ sclerometric tests, using the average of the values presented in Figure 8. The remaining parameters were derived from empirical relationships and reference values. These values were used to define the stiffness properties of a simplified model (Figure 8), which served to establish initial correlations between the measured data and the preliminary numerical simulation. This approach is intended as a first step toward the development of a more detailed model capable of accurately capturing the structural dynamics of the pyramid.

Table 3. Simplified model. Geometry and stiffness

Section	Height (h) m	Width (d) m	Length (L) m	Area (As) m ²	Volume (V) m ³	Weight (W) t	Lateral Stiffness t/cm
1	6.2	36.0	36.0	1296	8003	14136	30476
2	6.2	31.0	31.0	961	5958	9523	22507
3	5.1	26.0	26.0	676	3448	5516	19247
4 (crown)	20.6	-	-	-	2000		

Lateral Stiffness was assumed given only by shear stiffness calculated as $K_s = \frac{G_c \cdot A_s}{3h}$. A comparison between the natural frequencies and mode shapes identified from experimental measurements and those obtained from the preliminary simplified model is presented below, with the aim of establishing an initial benchmark for the development of a more refined and comprehensive numerical model. Table 4. Comparison between model and ambient vibration test results.

Mode	Modal Freq. [Hz] Model	Modal Freq. [Hz] Measured	Error [%]	Predominant Direction Modal Shape (Model and Measured)
1	4.07	4.07	0.00	Bending
2	9.54	9.99	4.50	Bending

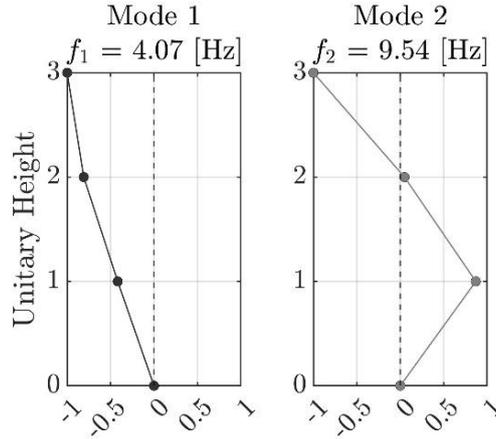


Figure 9. Modal shapes (2D). Simplified Model (3-DOF).

4. CONCLUSIONS

This study provides a comprehensive structural assessment of Temple II, focusing on its dynamic properties, geometric assessment, and material characteristics. Ambient vibration testing allowed for identifying modal frequencies, damping ratios, and mode shapes, providing a valuable understanding of the temple’s dynamic response. High-precision 3D laser scanning enabled the detection of differential settlements and an evaluation of the structure’s verticality. The point cloud analysis revealed that Temple II exhibits differential settlement along one of its principal directions, with displacements reaching up to 278 mm. This deformation corresponds to a tilt angle of 0.43° , indicating a measurable deviation from vertical alignment. Schmidt Hammer tests revealed significant variability in material strength, with an average compressive strength of 6.6 MPa. However, the results indicate high heterogeneity, with values ranging between 4 and 12 MPa. Despite this variability, the findings are consistent with the studies of M. Krzan [13], supporting the correlation between rebound number and compressive strength and reinforcing the reliability of Schmidt Hammer testing as a non-destructive method for assessing masonry materials. Additionally, a simplified computational model was developed and calibrated using experimental data, ensuring an acceptable representation of the temple’s structural dynamics characterization.

The findings highlight potential risks associated with differential settlements, suggesting the necessity of long-term monitoring. These preliminary evidence also emphasize the need for a more representative characterization of the strength of the structural materials and continuous and long-term monitoring of the temple’s dynamic properties and verticality. A more detailed assessment of the potential soil-structure interaction is recommended to better understand its influence on the observed settlement patterns and overall structural stability.

The current research reaffirms the importance of integrated monitoring approaches for the structural health assessment of heritage sites. The combination of ambient vibration testing, geometrical surveys (laser scanning), and non-destructive material evaluation provides a robust framework for assessing structural integrity while minimizing the risks of the Temple. Tracking changes over time is particularly valuable for early deterioration detection, allowing for preventive conservation strategies before significant damage occurs. This study also demonstrates the applicability of this multi-approach with valuable information for preserving heritage sites.

Based on these findings, several key recommendations can be made for future assessments of Temple II and comparable historic structures. First, the implementation of a continuous monitoring system using permanent sensors to obtain dynamic variations and detect long-term degradation patterns. Further research on soil-structure interaction would provide deeper insights into the causes and implications of the observed differential settlements. Advancing digital modelling techniques, mainly through digital twins and parametric simulations, would enhance predictive analysis and support conservation decision-making. Expanding this methodology to assess adjacent temples in Tikal could offer a broader

perspective on the structural evolution of the ancient city. Additionally, incorporating extreme event simulations, such as seismic loading and severe environmental conditions, would improve risk assessment and mitigation strategies for long-term conservation efforts.

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CREDIT AUTHORSHIP CONTRIBUTION STATEMENT

M. Motamedi: Leading site measurements, data curation, data processing. T. Nunez: Original draft, software, analysis, data processing, writing, investigation. V. Carol: Sclerometer data, project administration, supervision, logistics and data curator. S. Hernandez: Site support, translation and logistics. D. Bautista: Site support and logistics. C. Ventura: Conceptualization, data curation, site measurements, project administration, investigation.

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